THREE ESSAYS ON THE IMPACTS OF UNCONVENTIONAL DRILLING ON EARLY LIFE HEALTH

A Dissertation

Presented to the Faculty of the Graduate School

of Cornell University

in Partial Fulfillment of the Requirements for the Degree of

Doctor of Philosophy

by

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August 2014

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Cornell University 2014

A recent assessment estimated that over 15 million Americans live within 1 mile of a gas well drilled since 2000 in 11 states. This dissertation studies the impacts of unconventional drilling on infant health in three of these 11 states.

The first chapter exploits the introduction of shale gas wells in Pennsylvania beginning in 2008. Using detailed location data on maternal address and GIS coordinates of gas wells, I examine singleton births to mothers residing close to a shale gas well from 2003-2010 in Pennsylvania. The introduction of drilling increased low birth weight and decreased term birth weight on average among mothers within 2.5 km of a well compared to mothers within 2.5 km of a future well. Adverse effects were also detected using measures such as small for gestational age and APGAR scores, while no effects on gestation periods were found. These results are robust to other measures of infant health, many changes in specification and falsification tests. These results do not differ across water source (i.e. public piped water vs. ground well water) and suggest that the mechanism is air pollution or stress from localized economic activity. These findings suggest that shale gas development poses significant risks to human health and have policy implications for regulation of shale gas development.

The second chapter focuses on oil and gas development in Colorado. Colorado provides a unique research environment given its long history of conventional oil and gas extraction and, most recently, shale gas development. This paper uses Colorado to explore health at birth implications of both unconventional and conventional forms of drilling. The immediate outcomes of interest are infant health at birth measures (term birth weight,

gestation length, low birth weight, premature birth and small for gestational age). To define exposure, I utilize detailed vital statistics and mother's residential address to define close proximity to drilling activity. Using a difference-in-differences approach, this paper compares health at birth of infants born to residences within 1 km of the well head versus 1-2 km to identify the impact of drilling. Exploiting both the inter-temporal and cross-sectional variance in the presence of resource extraction in Colorado, I find that proximity to wells reduces birth weight and gestation length on average and increases the prevalence of low birth weight, premature birth and small for gestational age.

The third chapter studies shale gas development in the Barnett Shale, in north-central Texas near Dallas-Fort Worth, which contains one of the largest and most active onshore gas fields. The Barnett Shale provides a unique research environment given that it is the place where unconventional drilling was used commercially and is also a densely populated urban center in the US. This paper uses the most extensive air monitoring network in any shale play in the US to study the impact of shale gas development on ambient air pollution, the impact of these pollutants on infant health and the direct relationship between shale gas wells and birth outcomes. The estimation strategy exploits the fact that the Barnett Shale conveniently splits the Dallas-Fort Worth region in half. Using a difference-in-differences approach, this paper compares health at birth and ambient air pollution for zip codes within the shale region versus those outside of it. The shale region is associated with increased formaldehyde, NO_x, Ozone, and SO_2 in the "boom" years of 2004-2012. The initial drilling phase (1998-2001) is associated with an increase in hazardous BTEX pollutants that does not persist over time. I find that living in a zip code within the shale gas region reduces birth weight and gestation length on average, with mixed effects for low birth weight and premature birth. The findings also suggest that NO_x, SO_2, formaldehyde and the BTEX chemicals associated with shale gas development have adverse impacts on birth outcomes.

These three states make up the majority of recent drilling activity and represent both rural and urban contexts. In all three states, I find that living near shale gas development reduces the endowment of health at birth.

BIOGRAPHICAL SKETCH

Elaine Lawren Hill was born on June 13, 1983 in Rochester, NY. Elaine earned her B.A. in Economics and Mathematics with honors at Oberlin College in 2005. After college, Elaine worked at Mathematica Policy Research in Princeton, NJ as a research assistant/programmer. In 2008, Elaine moved to Ithaca, NY and began taking the PhD microeconomic theory sequence as an unmatriculated student. Meanwhile, she became a staff member of Cornell University. In 2009, Elaine entered the Ph.D program in Applied Economics and Management at Cornell University.

To my parents and my husband, Sudhir

ACKNOWLEDGEMENTS

Preparation of this dissertation would not have been possible if I had not received help from faculty, students, family, and friends. I also greatly benefited from all that Cornell has to offer its graduate community. It would be impossible to acknowledge every person or institution that contributed towards the preparation of this dissertation, so the following list is by no means complete.

I would like to extend my most heartfelt gratitude to my husband for his unceasing love and consistent support throughout the dissertation phase of my Ph.D. He has taught me the love of research, the joy of hard work, and the excitement of academe. Additionally, my parents and my brothers have been an unwavering source of support, love, and inspiration during the PhD as well as throughout my entire life. In particular, my parents' sacrifice so that my brothers and I could pursue any educational dream made this all possible. My grandparents first encouraged me to follow my dreams and were role models of excellence.

My dissertation committee, comprised of David Sahn, John Cawley and George Jakubson, has expertly guided me throughout the process while providing critical comments that have enhanced the quality of my research. In particular, I would like to acknowledge the critical role that David Sahn has had in the unfolding of my research. Thank you, David, for encouraging me to study a topic outside of the original plan and to take a risk to become the health economist I was meant to be. I am grateful for your clear guidance and for helping me to gain access to the necessary resources. I'd also like to thank you for taking me with you to India- it changed my life. I owe you so much. Thank you to John Cawley for first introducing me to health economics and the many amazing opportunities that health economists have for employment and research areas. John, you have been invaluable in the process and I'm particularly grateful for your support during the job market. Thank you to George Jakubson for giving me a solid foundation in econometrics and for always having your door wide open. Gratitude to Jordan Matsudaira for being an informal mentor: thank you, Jordan, for your open door policy and for helping me find my way.

I would like to thank the department of Policy Analysis and Management for offering me TA-ships and Miguel Gomez for offering me an amazing research assistantship that allowed me to participate in a large, multi-disciplinary project. Miguel, you have been a steady support and I have gained so much from working with you over these past three years. I would like to thank the Cornell Population Center for their financial support for my research. Without them, I would not have access to the data used throughout my dissertation. The CPC is an amazing resource for graduate students and truly made my experience at Cornell a memorable one.

During these years, I have been fortunate to have connected with amazing people in Ithaca, NY. Many of my friends have been in the classroom and many have been found in a yoga studio. I would like to acknowledge a few by name who have had a special place in my heart: Kira Villa, Gabi Salazar, Taryn Thompson, Jenny Chorba, Ammitai Worob, Ann Greenberg, John Skrovan, Rachel Bush, Amy Abelson, Sophie Trowbridge, Leslie Verteramo and Julia Berazneva. Dearest Joanna Upton– it's been an amazing ride– to Uganda and to our home at 725 W Court St. I am so grateful for your friendship and that I had the opportunity to share our home with you. These last three years definitely wouldn't have gone so smoothly without you. The staff of AEM, especially Linda Sanderson, have provided crucial and amazing support.

My colleagues away from Cornell have also provided invaluable comments on the research that follows. Gratitude to Jordan Suter, David Slusky, Alison Buttenheim, David Goldsmith, Nick Sanders, Reed Walker, Matt Neidell, Seth Berrin Shonkoff, Doug Almond, Chris Timmins, Jeremy Weber and Lucija Muehlenbachs. I look forward to many future opportunities to engage in research with you.

I would like to thank Kirk Bol at the Colorado Department of Public Health and the Environment for access to the vital records and for providing necessary data support. Thank you to Amy Farrell and James Rubertone at the Pennsylvania Department of Health for providing access to the restricted vital records. Thank you to Doneshia Ates of the Texas Department of State Health Services for providing access to the vital records.

The data were supplied by the Bureau of Health Statistics & Research, Pennsylvania Department of Health (PDOH), Harrisburg, Pennsylvania, the Colorado Department of Public Health and the Environment (CDPHE) and the Texas Department of State Health Services (TDSHS). The PDOH, CDPHE and TDSHS specifically disclaims responsibility for any analyses, interpretations or conclusions. All errors are mine alone.

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CHAPTER 1

INTRODUCTION

The United States (US) holds large unconventional gas reserves in relatively impermeable media such as coal beds, shale, and tight gas sands, which together with Canada account for virtually all commercial shale gas produced in the world (IEA, 2012). New technologies, such as hydraulic fracturing and directional drilling, have made it economically and practically feasible to extract natural gas from these previously inaccessible geological formations. Hydraulic fracturing (popularly known as "fracking" or "fracing") stimulates the well using a combination of large quantities of water ("high-volume"), fracturing chemicals ("slick water") and sand that are injected underground at high pressure. This process fractures the rock and causes the resource to be released. In 2010, unconventional gas production was nearly 60% of total gas production in the US (IEA, 2012). As of 2011, there are over 1 million actively producing natural gas wells and it is estimated that over 11,000 unconventional gas wells are drilled each year in the US (IEA, 2012).

The expansion of shale gas development in the US has brought with it a national debate that seemingly lacks a consensus over its economic, environmental, health and social implications. Shale gas has been promoted as a low-cost source of electricity, residential and commercial energy, industrial feed stocks, and even as transportation fuel. Natural gas provides an attractive source of energy because it emits fewer pollutants (e.g., carbon dioxide, sulfur dioxide, nitrogen oxides, carbon monoxide and particulate matter) when burned than other fossil-fuel energy sources per unit of heat produced. There is growing evidence that natural gas development creates jobs and generates income for local residents in the short run (Weber, 2011; Marchand, 2012). Other studies have shown that housing prices for those homes on public water increase in close proximity to drilling in Pennsylvania and New York from increased economic activity, but that perceived risks of ground water contamination reduces housing prices for homes that use well water

(Muehlenbachs et al., 2014).[1] The benefits of domestically sourced natural gas have been at the forefront of a public debate, even mentioned by President Obama in his 2012 and 2013 State of the Union Addresses as an initiative of his administration.

The focus of the other side of this debate, however, is the potential environmental impacts —and subsequent public health implications— of shale gas development. Shale gas development is currently exempted from the Safe Drinking Water Act, Clean Air Act, and Clean Water Act regulations. Serious environmental and health concerns have nonetheless emerged regarding drilling activity (COGCC and Commission, 2009). The opposition to shale gas development cites recent studies reporting methane leakage (Howarth et al., 2011; Hultman et al., 2011), local air pollution (Litovitz et al., 2013; Colborn et al., 2012; Witter et al., 2013; Bunch et al., 2014; Moore et al., 2014; Zavala-Araiza et al., 2014), water pollution (Olmstead et al., 2013; Warner et al., 2012; DiGiulio et al., 2011; Osborn et al., 2011; EPA, 2004; DEP, 2009; Lyverse and Unthank, 1988), and increased truck traffic (Considine et al., 2011; ALL Consulting, 2010). Preliminary evidence indicates that shale gas development may produce waste that could contaminate the air, aquifers, waterways, and ecosystems that surround drilling sites or areas where water treatment facilities treat the waste water from the drilling process. However, there is little consensus about the likelihood of contamination, mechanisms or how widespread it might be. For water pollution, faulty well casings or surface spills and accidents are considered the least controversial pathways (Osborn et al., 2011). Despite less attention in the media, air pollution is gaining more recent attention by researchers; sources of air pollution are expected with combustion activities, methane flaring and truck traffic (Witter et al., 2013; EPA, 2011; Bunch et al., 2014; Moore et al., 2014; Zavala-Araiza et al., 2014).

[1] Gopalakrishnan and Klaiber (Forthcoming) found reduced housing prices associated with the introduction of shale gas development in Washington County, PA; the effects fell disproportionately on rural homes that rely on ground water.

Inferring from the environmental concerns, a few recent studies have assessed the potential health effects of unconventional methods using case studies, health impact assessments and toxicology to show that there are likely to be short and long term negative health effects (Bamberger and Oswald, 2012; McKenzie et al., 2012; Colborn et al., 2011).[2] While the public health literature has suggested that human health might be affected by exposures to shale gas development, and there have been numerous anecdotal accounts and suspicions, this dissertation is the first set of studies to rigorously link shale gas development to human health outcomes.[3]

Discussion of Distances and Identification

This dissertation is composed of three chapters exploring unconventional, and in the case of Colorado conventional, drilling activity in three different states and contexts. Due to differences in data quality, drilling timing and intensity, the exact identification strategies differ. This is consistent with the economic literature that uses slightly dif-

[2]Unconventional drilling brings with it complex chemicals used in the "fracturing fluid," causing public health concerns of ground water contamination. These chemicals are small in proportion to the quantity of fresh water, but are associated with many negative health effects if ingested or inhaled, such as cancers, nervous system impairment and impaired lung function (Colborn et al., 2011).There have been a wide range of claims and anecdotal evidence of negative effects on human and animal health, including a wide range of health-related symptoms. For example, Lisak (2013) has compiled a list of 1384 people and families (as of June 2013) who believe they have been harmed by shale gas production in the US. Each person/family reported lists details regarding the type of gas facility, the location, the believed exposure (air, water, etc.) and symptoms as well as any media reports related to the individual/family. Other examples include many local media reports and the "Drilling Down" series by Ian Urbina of the New York Times which examines the risks of shale gas development (Urbina, 2011). More recently, researchers from the University of Pittsburgh documented self-reported health impacts and health stressors perceived from shale gas development in Pennsylvania (Ferrar et al., 2013).

[3]McKenzie et al. (2014), a study published concurrently to this work, estimated that prevalence of congenital heart defects (CHDs) increased and neural tube defects prevalence was associated with the highest tertile of exposure compared with the absence of any gas wells within a 10-mile radius. Exposure was negatively associated with preterm birth and positively associated with fetal growth, although the magnitude of the association was small.

ferent distances to estimate impacts of various "treatments". For example, Currie and Walker (2011) use residences within 1.5 km of a toll booth compared to residences 1.5-10 km away from a toll booth to identify the causal impact of the introduction of EZ-Pass on infant health in NJ and PA. Currie et al. (2011) use 2 km compared to 2-5 km from a superfund site. More recently, Currie et al. (2013a) use 1 mile (approximately 1.6 km) from toxic plants to identify the impact on infant health of toxic plant closures. McKenzie et al. (2012) estimated air pollution health effects from shale gas development in Colorado within 0.5 miles (or 0.8 km) and Colborn et al. (2012) measured air pollution 1.1 km from the well head in Colorado.[4] McKenzie et al. (2014) estimated the impact of shale gas development on birth defects within 10 miles of the mother's residence. These discrepancies are driven by a lack of research informing the distance at which exposures dissipate. According to the EPA, some air pollutants can travel as little as a hundred yards or as far as 30 miles.

Table 1.1 contains a comparison of the three papers in this dissertation. The distances chosen for the first two papers were driven by the data due to the lack of a theory or a model for the exact mechanism of exposure (air, water, stress, etc.). In the case of Pennsylvania, the distance chosen was 2.5 km, which is where the sample size became large enough to estimate consistent results. Within 1 km in the Pennsylvania sample, the distance chosen in Colorado, there were only 300 infants born after drilling began. This small sample size is primarily a function of the fact that only about 1 year of data is available after drilling began. In contrast, in Colorado, there were close to 10,000 infants born within 1 km due to the historical nature of drilling activity in that state, which gave more statistical power to detect differences at a closer proximity. In both papers, I provide graphical evidence supporting the distances used, as well as, estimate different distance bins and report these in the appendixes. Ultimately, Pennsylvania and Colorado have very different climates, elevation, and weather patterns, which may also drive the differ-

[4]These distances are very consistent with the distances used in Chapter 3 which compares 1 km to 1-5 km, before and after drilling.

ences detected in the data. Chapter 4 is the most unique due to the lack of exact maternal address in the vital statistics data and is geocoded at the zip code level. I made use of the geology (where the Barnett Shale is) to form treatment and control groups and compared zip codes within the Dallas-Fort Worth Metro based upon whether they are on or off the shale. Therefore, the counterfactual for each of these papers is somewhat different. The choices of estimation strategy are internally valid but may highlight the need for location-specific studies to understand how far from drilling activity individuals may be impacted in other states.

Chapter 2 Pennsylvania

The first case study exploits the introduction of shale gas wells in Pennsylvania which began in 2008. Using detailed location data on maternal address and GIS coordinates of gas wells, I examine singleton births to mothers residing close to a shale gas well from 2003-2010 in Pennsylvania. To define a treatment variable, I exploit both the timing of drilling activity (using the "spud date," or the date the drilling rig begins to drill a well) and the exact locations of wells relative to residences. I then use, as a comparison group, mothers who live in close proximity to future wells as designated by well permits. The exact locations of both wells and mothers' residences allow me to exploit variation in the effect of gas drilling within small, relatively homogenous socio-economic groups, and the timing of the start of drilling allows me to confirm the absence of substantive pre-existing differences.

Through this method, I find that the introduction of drilling increased low birth weight and decreased term birth weight on average. Adverse effects were also detected using measures such as small for gestational age and APGAR scores, while no effects on gestation periods were found. Using public water service areas to define maternal residences that receive piped public water versus maternal residences that use well (ground) water, I do not find differences in adverse birth outcomes between these two groups. This is suggestive evidence that the mechanism is not through the exposure pathway of water.

I find some weakly suggestive evidence that mothers may be more likely to move after drilling but there does not appear to be any evidence that higher SES mothers are systematically more likely to move in response to drilling activity. Using a mother fixed effects model, I find qualitatively similar results and I do not find differential effects for those who stay versus those who move, which provides evidence that the research design is robust to changes in maternal mobility, fertility or behavior in response to drilling activity. I find that effects of gas drilling are larger for lower SES children.

Though exact mechanisms are difficult to ascertain with the data currently available in Pennsylvania, the increase in small for gestational age and low birth weight without a symmetric increase in premature birth indicates that infants born to mothers exposed to drilling are coming to full term, but are small. Thus, exposures to drilling activity are suggestive of intrauterine growth restriction (measured by small for gestational age or the <10th percentile of birth weight for gestational age), which has not been definitively linked in the literature to particulates, but instead indicative of high levels of polycyclic aromatic hydrocarbons (Glinianaia et al., 2004; Bobak, 2000; Sram et al., 2005).[5] Low birth weight, in contrast, has been linked to many of the measured air pollutants associated with gas drilling and is indicative of exposures to benzene, particulates, SO_2, NO_x, and VOCs (amongst others).

These results are robust to other measures of infant health, many changes in specification and falsification tests. These results do not differ across water source (i.e. public piped water vs. ground well water) and suggest that the mechanism may be air pollution or stress from localized economic activity. These findings suggest that shale gas develop-

[5]Colborn et al. (2012) measured high levels of polycyclic aromatic hydrocarbons 1.1 km from a well pad in Western Colorado.

ment poses significant risks to human health and have policy implications for regulation of shale gas development such as requiring air pollution monitoring of drilling sites.

Chapter 3 Colorado

The second chapter focuses on oil and gas development in Colorado. Colorado provides a unique research environment given its long history of conventional oil and gas extraction and, most recently, shale gas development. To date, no study on infant health effects across resource extraction types (oil, shale gas, conventional natural gas and coal bed methane) or historical drilling exists. Colorado provides a unique environment to explore multiple extraction activities. This chapter uses Colorado to explore health at birth implications and risks associated with conventional and unconventional forms of drilling. Hydraulic fracturing has become prevalent in the last decade and according to the Colorado Oil and Gas Conservation Commission (COGCC), all of the $50,030$ oil and gas wells in Colorado were hydraulically fractured (as of June 2013). In this chapter, I combine data on oil, gas and coal bed methane extraction from the Colorado Oil and Gas Conservation Commission (COGCC) with data from birth certificate records from the Colorado Department of Public Health and Environment (CDPHE) to estimate the infant health impacts of living in close proximity to a well during pregnancy. To define exposure, I utilize detailed vital statistics and mother's residential address to define close proximity to drilling activity. Using a difference-in-differences approach, this paper compares health at birth of infants born to residences within 1 km of the well head versus 1-5 km to identify the impact of drilling.

Exploiting both the inter-temporal and cross-sectional variance in the presence of resource extraction in Colorado, I find that very close proximity to wells reduces birth weight and gestation length, on average and increases the prevalence of low birth weight, premature birth and small for gestational age. The results for maternal risk factors are suggestive of increased stress and exposure to ambient air pollution. These results begin to clarify the likely mechanisms that explain the infant health results. I also find that the results for different levels of low birth weight and premature birth suggest that oil and gas extraction are not merely increasing those that fall below the threshold (of low birth weight or prematurity), but that there is also an increase in very low birth weight and very premature birth. This suggests that the communities exposed may experience increased infant mortality and certainly higher health care costs associated with these more vulnerable infants. Finally, these results suggest that conventional drilling practices are likely to adversely impact birth outcomes, not just shale gas development ("fracking").

Chapter 4 Texas

The third chapter studies shale gas development in the Barnett Shale, in north-central Texas near Dallas-Fort Worth, which contains one of the largest and most active onshore gas fields. The Barnett Shale provides a unique research environment given that it is the first shale play where commercial hydraulic fracturing was used to extract natural gas and is also a densely populated urban center in the US. This chapter uses the most extensive air monitoring network in any shale play in the US to study the impact of shale gas development on ambient air pollution, the impact of these pollutants on infant health and the direct relationship between shale gas wells and birth outcomes. The estimation strategy exploits the fact that the Barnett Shale conveniently splits the Dallas-Fort Worth region in half. Using a difference-in-differences approach, this paper compares health at birth and ambient air pollution for zip codes within the shale region to those outside of it. Although I do not have the exact address for the mothers in this study, I am able to instead capture more community level effects, as opposed to the very localized effects measured in the first two chapters.

My results suggest that shale gas development can have adverse effects on the health of people living in a shale region, namely that of prenatal infants. Shale zip codes had higher incidence of low birth weight and premature birth in the earliest years of development. Low birth weight also increased for the mid-development years of 2001-2004. Furthermore, term birth weight was decreased on average for the years 2001-2008. Gestation was reduced over the entire time frame studied.

I also found that shale gas development can have a measurable impact on ambient air quality. Shale zip codes during the peak development period (2004-2008) experienced higher NO_2, NO_x, SO_2, and formaldehyde. Shale zip codes during the moderate drilling and peak production period (2009-2011) experienced higher CO, Ozone, PM_{10}, and formaldehyde. BTEX chemicals had the largest increase in the shale region during the initial drilling phase (1998-2001) but these increases do no persist.

My findings indicate that the pollutants increased by shale gas development have a direct impact on health at birth outcomes. The pollutants studied (NO_x, SO_2, formaldehyde and the BTEX chemicals) had strong and significant adverse effects on the four birth outcomes studied. These relationships are detected in both the trimester and gestation models (only gestation models are reported).

This study shows the direct link between shale gas, ambient air pollution and birth outcomes. These results suggest that requiring air pollution monitoring of drilling sites could assist researchers and public health officials in efforts to ascertain exposure pathways for residents living nearby and inform policies to mitigate any risks that are likely to be very localized. Despite the Barnett Shale being under an urban metro where there are many sources of air pollution, there are still detectable adverse impacts of shale gas development on both air quality and infant health.

Conclusion

The three states studied in this dissertation make up the majority of recent drilling activity and represent both rural and urban contexts. In all three states, I find that living near unconventional drilling reduces the endowment of health at birth. In Pennsylvania, I find that living in close proximity to shale gas development has an adverse impact on birth weights, while in Colorado and Texas, states with longer term development, I also find impacts on gestation and premature birth. The Colorado context highlights the fact that there are impacts for conventional oil and gas development, as well, not just unconventional drilling such as shale gas. The magnitudes of the impacts in this dissertation are very similar in magnitude to those in other studies of air pollution and infant health (Zahran et al., 2012; Slama et al., 2009). In Pennsylvania, I find that there are no differences in impacts for maternal residences that receive public piped water versus those that use ground water, which suggests that water source is not likely to be the primary mechanism driving these results. This is further supported by the findings in Texas that shale gas development has a direct impact on ambient air quality. It is clear from these results that policies intended to mitigate the risks of shale gas development can have significant health benefits. These findings add to the impetus for regulators to increase regulations that reduce air pollution emissions from drilling operations and for industry actors to increase voluntary action to reduce air pollution emissions. Given the wealth of studies that identify a causal link between birth weights and long-run outcomes, these impacts are likely to persist throughout these children's lives and indicate that further research investigating later life impacts of shale gas development is needed (Johnson and Schoeni, 2011; Black et al., 2007).

Table 1.1: Comparison: Distances, Identification and Results

	Chapter 2: Pennsylvania	Chapter 3: Colorado	Chapter 4: Texas
Treatment Group	Within 2.5 km of shale gas well, after drilling	Within 1 km of oilgas well after drilling	Zip codes on the Barnett Shale
Control Group	Within 2.5 km of shale gas well, before drilling (permits)	1-5 km of oilgas well before and after drilling	Zip codes not on the Barnett Shale
I.A.	In the absence of treatment, the unobserved differences between T and C are the same over time		
Results	Decreased TBW (49 grams) and increased LBW by 25%	Decreased TBW (36 grams) and gestation, and increased LBW and premature birth by 31% and 33%, respectively	Decreased TBW (20 grams) and gestation, and increased LBW by 10%
Falsification Tests	Permit dates and random dates	Permit dates and random dates	Zip codes with wells in zip code boundary

Notes: TBW= Term Birth Weight; LBW= Low Birth Weight; I.A. = Identifying Assumption. For further information about falsification tests, please see respective chapters. For Chapter 4, I only study those zip codes in the Dallas-Fort Worth metro.

CHAPTER 2

SHALE GAS DEVELOPMENT AND INFANT HEALTH: EVIDENCE FROM PENNSYLVANIA

2.1 Introduction

The United States (US) holds large unconventional gas reserves in relatively impermeable media such as coal beds, shale, and tight gas sands, which together with Canada account for virtually all commercial shale gas produced in the world (IEA, 2012).[1] New technologies, such as hydraulic fracturing and directional drilling, have made it economically and practically feasible to extract natural gas from these previously inaccessible geological formations.[2] In 2010, unconventional gas production was nearly 60% of total gas production in the US (IEA, 2012). Natural gas from the Marcellus formation, particularly in Pennsylvania, currently accounts for the majority of this production (Rahm et al., 2013).[3]

The expansion of shale gas development in the US has brought with it a national debate that seemingly lacks a consensus over its economic, environmental, health and social implications. Shale gas has been promoted as a low-cost source of electricity, residential and commercial energy, industrial feed stocks, and even as transportation fuel. Natural gas provides an attractive source of energy because it emits fewer pollutants (e.g., carbon dioxide, sulfur dioxide, nitrogen oxides, carbon monoxide and particulate mat-

[1]The International Energy Agency (IEA) defines unconventional gas as sources of gas trapped in impermeable rock deep underground.

[2]Hydraulic fracturing (popularly known as "fracking" or "fracing") stimulates the well using a combination of large quantities of water ("high-volume"), fracturing chemicals ("slick water") and sand that are injected underground at high pressure. This process fractures the rock and causes the resource to be released.

[3]Pennsylvania experienced very rapid development of shale gas, with 4,272 shale gas wells drilled from 2007-2010 (PADEP, 2010a).

ter) when burned than other fossil-fuel energy sources per unit of heat produced. As mentioned above, it also comes predominantly from reliable domestic sources and has resulted in many landowners receiving high resource rents for the hydrocarbons beneath their land.[4] There is growing evidence that natural gas development creates jobs and generates income for local residents in the short run (Weber, 2011; Marchand, 2012). Other studies have shown that housing prices for those homes on public water increase in close proximity to drilling in Pennsylvania and New York, but that perceived risks of ground water contamination reduces housing prices for homes that use well water (Muehlenbachs et al., 2014).[5] The benefits of domestically sourced natural gas have been at the forefront of a public debate, even mentioned by President Obama in his 2012 and 2013 State of the Union Addresses as an initiative of his administration. In addition to its economic benefits, many claim that a move to natural gas development (and away from petroleum-based energy) will support U.S. energy independence and national security.

The focus of the other side of this debate, however, is the potential environmental impacts –and subsequent public health implications– of shale gas development. Shale gas development is currently exempted from the Safe Drinking Water Act, Clean Air Act, and Clean Water Act regulations. Serious environmental and health concerns have nonetheless emerged regarding drilling activity (COGCC and Commission, 2009). The opposition to shale gas development cites recent studies reporting methane leakage (Howarth et al., 2011; Hultman et al., 2011), local air pollution (Litovitz et al., 2013; Colborn et al., 2012; Witter et al., 2013), water pollution (Olmstead et al., 2013; Warner et al., 2012; DiGiulio et al., 2011; Osborn et al., 2011; EPA, 2004; DEP, 2009; Lyverse and Unthank, 1988), and increased truck traffic (Considine et al., 2011; ALL Consulting, 2010). Inferring from the

[4]Upon signing their mineral rights to a gas company, landowners may receive hundreds or even thousands of dollars per acre as a bonus payment, and then a per unit (mcf) royalty of gas extracted.

[5]Gopalakrishnan and Klaiber (Forthcoming) found reduced housing prices associated with the introduction of shale gas development in Washington County, PA; the effects fell disproportionately on rural homes that rely on ground water.

environmental concerns, a few recent studies have assessed the potential health effects of unconventional methods using case studies, health impact assessments and toxicology to show that there are likely to be short and long term negative health effects (Bamberger and Oswald, 2012; McKenzie et al., 2012; Colborn et al., 2011).[6] While the public health literature has suggested that human health might be affected by exposures to shale gas development, and there have been numerous anecdotal accounts and suspicions, this is the first study to date rigorously linking shale gas development to human health outcomes.[7]

This paper takes a step toward addressing the gap in the literature by using data that contains the longitude and latitude of all shale gas wells, the street address (geocoded) of all new mothers, and data on whether the mother's address falls within public water service areas to estimate the impacts on infant health of shale gas development. To define a treatment variable, I exploit both the timing of drilling activity (using the "spud date,' or the date the drilling rig begins to drill a well) and the exact locations of well heads relative to residences. I then use as a comparison group mothers who live in proximity to future wells, as designated by well permits. The exact locations of both wells and mothers'

[6]These studies do not measure actual health effects, but use other methods to infer the potential for harm to human health. Shale gas development brings with it complex chemicals used in the "fracturing fluid," causing public health concerns of ground water contamination. These chemicals are small in proportion to the quantity of fresh water, but are associated with many negative health effects if ingested or inhaled, such as cancers, nervous system impairment and impaired lung function. See Colborn et al. (2011) regarding health effects of fracturing chemicals; see McKenzie et al. (2012) for a review of studies investigating the effects of inhalation exposure.

[7]There have been a wide range of claims and anecdotal evidence of negative effects on human and animal health, including a wide range of health-related symptoms. For example, Lisak (2013) has compiled a list of 1384 people and families (as of June 2013) who believe they have been harmed by shale gas production in the US. Each person/family listed is associated with details regarding the type of gas facility, the location, the believed exposure (air, water, etc.) and symptoms as well as any media reports related to the individual/family. Other examples include many local media reports and the "Drilling Down" series by Ian Urbina of the New York Times which examines the risks of shale gas development (Urbina, 2011). More recently, researchers from the University of Pittsburgh documented self-reported health impacts and health stressors perceived from shale gas development in Pennsylvania (Ferrar et al., 2013).

residences allow me to exploit variation in the effect of gas drilling within small, relatively homogenous socio-economic groups, and the timing of the start of drilling allows me to confirm the absence of substantive pre-existing differences. Through this method, I am able to provide the first robust estimates of the impact of maternal exposure to shale gas development on birth outcomes.

The main results suggest both statistically and economically significant effects on infant health. I find that shale gas development increased the incidence of low birth weight and small for gestational age in the vicinity of a shale gas well by 25 percent and 18 percent, respectively. Furthermore, term birth weight and birth weight were decreased by 49.6 grams (1.5 percent) and 46.6 grams (1.4 percent), on average, respectively and the prevalence of APGAR scores less than 8 increased by 26 percent. No changes in gestation or premature birth were detected. The difference-in-differences research design, which relies on the common trends assumption, is tested by examining the observable characteristics of the mothers in these two groups before and after development. The research design is robust to a range of specifications. I also test whether these results vary by water source, given the concerns around shale gas development and ground water contamination. The results do not differ across water source (i.e. public piped water vs. ground well water) and suggest that the mechanism is air pollution or stress from localized economic activity. Additionally, I estimate a mother fixed effects model and find consistent results.

2.2 Background

2.2.1 Shale Gas Overview

In Pennsylvania, shale gas development involves both vertical and horizontal wells drilled primarily into the Marcellus Shale, but more recently, the Utica Shale. The drilling process includes a technique to stimulate the wells called hydraulic fracturing. Hydraulic fracturing is a process that uses water to fracture the rock or shale beneath the ground. On average, in Pennsylvania, it involves injecting 3-4 million gallons of water mixed with sand and fracturing chemicals into the well and using pressure to fracture the shale about 7,000 ft below the surface (ALL Consulting, 2009). Shale plays are heterogeneous and so the distance drilled and quantity of water required differs across varied geological formations.

The entire process of completing a natural gas well takes, on average, 3-4 months to finish.[8] During the first month, diesel trucks bring in materials required for the drilling process, averaging 1500-2000 truck trips per well completion in Pennsylvania (ALL Consulting, 2010). During the first 30 days after well completion, it is estimated that approximately 30-70% of the water used during the drilling process returns to the surface (called flowback) and is collected in ground level water impoundments and then taken to be treated at a waste water facility (ALL Consulting, 2009).

Most wells are drilled on private property that has been leased to oil and gas companies.[9] There are a growing number of wells being drilled on public BLM lands, due to the push for more domestically sourced natural gas. After the land is leased by the mineral

[8]Due to improved drilling technology, this time to completion was greatly reduced in 2011 to approximately 1 month.

[9]To date, there are no estimates in Pennsylvania of how many properties are "split estate"- the condition where surface owners do not own the mineral rights.

owner, a company applies for a permit to drill on that property. The state government approves permits and once a company has a permit, the drilling often commences quickly thereafter. There are many layers of decision-making independent of the mineral owner that determine exactly which leases become permits and which permits become a well. This research uses only those locations that are permitted by the state to reduce selection bias in the estimates that follow.

2.2.2 Shale Gas Development As A Potential Pollution Source

Preliminary evidence indicates that shale gas development may produce waste that could contaminate the air, aquifers, waterways, and ecosystems that surround drilling sites or areas where water treatment facilities treat the waste water from the drilling process. However, there is little consensus about the likelihood of contamination, mechanisms or how widespread it might be. For water pollution, faulty well casings or surface spills and accidents are considered the least controversial pathways (Osborn et al., 2011).[10] Despite less attention in the media, air pollution is gaining more recent attention by researchers; sources of air pollution are expected with combustion activities, methane flaring and truck traffic (Witter et al., 2013; EPA, 2011).

Ground and Surface Water Contamination

Much of the concern identified in the media around unconventional drilling methods, and specifically the method of hydraulic fracturing, relates to potential human exposure due to ground water contamination (Urbina, 2011). According to a Congressional report, between 2005 and 2009, the 14 oil and gas service companies reportedly used more than

[10] With virtually no pre-drilling samples of water wells near drilling sites, most studies are not considered conclusive.

2,500 hydraulic fracturing products containing 750 chemicals and other components (Energy Commerce Committee, 2011). Of these 2,500 products, 650 contained 29 chemicals that are either 1) known or possible human carcinogens 2) regulated under the Safe Drinking Water Act for their risks to human health or 3) listed as hazardous air pollutants under the Clean Air Act. The most widely used chemical was methanol, a known hazardous air pollutant. The BTEX compounds –benzene, toluene, ethylbenzene and xylene– appeared in 60 of the hydraulic fracturing products used between 2005 and 2009. BTEX compounds are known human carcinogens. The gas companies reportedly injected 11.4 million gallons of products containing at least one BTEX chemical over the five year period reported. These chemicals are used in small proportion (0.5-2%) to the quantity of fresh water used in the drilling process and so skepticism exists regarding how susceptible aquifers are to contamination (ALL Consulting, 2009). A report by the US Environmental Protection Agency showed that if BTEX was used, then the concentration of BTEX at the point of injection would be 45-4,400 ppb for benzene, 120-31,000 ppb for toluene, 120-8,700 ppb for ethylbenzene and 330-26,000 ppb for xylene (EPA, 2004). And with chemicals like benzene considered hazardous to human health at 5 ppb (0.005mg/L), these concentrations are considered very high, but the report concluded that the risk to groundwater sources was minimal due to mitigation techniques of dilution, dispersion and degradation (EPA, 2004).

In the current literature, the two least controversial pathways of ground water contamination are faulty well casings or from abandoned wells nearby (Osborn et al., 2011; Jackson et al., 2013; EPA, 2004; DEP, 2009; Lyverse and Unthank, 1988).[11] More controversial sources of ground water contamination are pathways between the shale formation and the aquifer, or if the drilling process occurs too close to a drinking water aquifer

[11] The PA DEP estimated that it only had records for 141,000 of 325,000 oil and gas wells drilled historically in the state, leaving the status and location unknown for approximately 184,000 abandoned wells (PADEP, 2000). The likelihood of abandoned wells being conduits of groundwater contamination in Pennsylvania remains unknown at this time.

(Warner et al., 2012; DiGiulio et al., 2011). Migration of brine is theoretically possible, given certain assumptions, but the likelihood remains debated in the literature (Myers, 2012; Saiers and Barth, 2012).

To date, there are only a few studies addressing ground water contamination concerns. One EPA study found that wells near drilling sites had elevated levels of methane, hydrocarbons associated with the shale play, and solvents used in the drilling process in wells tested near Pavilion, Wyoming (DiGiulio et al., 2011).[12] Another recent study, using a sample of 60 water wells in Northeastern, PA, found that drinking-water wells within a 1 km radius of a well head had methane concentrations 17 times higher than wells outside of the 1 km radius, with no measurable contamination of brine or fracturing fluids (Osborn et al., 2011).[13] The authors sampled an additional 81 water wells to enhance their previous findings and found methane in water wells 82 percent of the time, with concentrations 6 times higher for homes less than 1 km from a shale gas well (Jackson et al., 2013).[14] The simplest explanations for their observations were faulty or inadequate steel casings and imperfections in the cement sealing. The Pennsylvania Department of Environmental Protection (PA DEP) issued 90 violations in 2010 and 119 violations in 2011 for faulty casing and cementing. Potential human health effects from drinking water contaminated with methane are not well understood.

Although surface water is more likely to be affected by drilling activity, from land-clearing, flow back water, and surface spills, few studies to date have assessed the risks associated with the treatment of flow back water (Krupnick et al., 2013). Olmstead et al.

[12]Due to mounting criticism regarding the report and the interpretation of its findings, USGS has released quality control well data with no interpretation and Pavilion, Wyoming is part of the large EPA study currently underway (Wright et al., 2012; EPA, 2012).

[13]The authors indicate that the presence of the well itself may be the conduit for methane migration, not necessarily the process of hydraulic fracturing.

[14]The authors also studied ethane and propane, two hydrocarbons that are only associated with gas extraction activities, and found that ethane was 23 times higher for homes less than 1 km from a gas well.

(2013) conducted a large-scale examination of the extent to which shale gas development affects surface water quality in Pennsylvania and determined that the treatment and release of waste water from shale gas wells increased prevalence of downstream concentrations of chloride. Total suspended solids (TSS) were increased by the presence of shale gas wells in the watershed, but the mechanism was indeterminate and perhaps related to spills, land-clearing or another un-known source of TSS related to the density of wells. Another recent study found elevated levels of radioactivity, salts and metals in river water and sediments at a site where treated water from oil and gas operations is discharged into a western Pennsylvania creek (Warner et al., 2013). The potential implications of these findings on surface drinking water sources have yet to be assessed.

Air Pollution

All stages of shale gas development have the potential to produce hazardous air pollution emissions (EPA, 2000, 2010, 2011; Kargbo et al., 2010; Schmidt, 2011). Air pollution has become a more immediate concern following some recent studies in Colorado that discovered higher levels of volatile organic compounds (VOCs), methane and other hydrocarbons near drilling sites (McKenzie et al., 2012; Colborn et al., 2012; Gilman et al., 2013; Pétron et al., 2012). Other emissions associated with combustion include particulate matter, polycyclic aromatic hydrocarbons, sulfur oxides and nitrogen oxides (Colborn et al., 2012; EPA, 2008).

Studies of air pollution in Pennsylvania are suggestive of increased emissions associated with shale gas development, but have produced inconsistent results. For example, the Pennsylvania Department of Environmental Protection (PA DEP) has conducted three short-term (1 week) air pollution studies in three regions of the state but found little evidence of air pollution concentrations that would likely trigger air-related health issues associated with Marcellus Shale drilling activities (PADEP, 2010b, 2011a,b). But the air emissions inventory for the unconventional natural gas industry, conducted for the year 2011, indicates modest emissions of CO, NO_x, PM_{10}, SO_x and VOCs (PADEP, 2013c). These results were verified by a recent RAND study that used the PA DEP data and other sources to estimate the emissions from shale gas in Pennsylvania (Litovitz et al., 2013). The most significant pollutants, according to the authors, were NO_x and VOCs, which were equivalent to or larger than some of the largest single emitters in the state and the low-end estimates of nitrogen oxide emissions were 20-40 times higher than the level that would be defined as a "major" emissions source. During the same time period, due to the conversion of electricity from coal to natural gas in the state, the overall pollution for all the criteria pollutants measured decreased substantially and more than outweighed the new pollution related to shale gas development. These data, however, indicate a more nuanced picture of air emissions from drilling activities and show that shale gas development is now a significant source of air pollution in rural counties with few other point-sources of pollution. For example, the 2,600 tons and 2,440 tons of shale-related NO_x emitted in Bradford County and Susquehanna County, respectively in 2011 make up one-third of the statewide shale-related NO_x of 16,500 tons (PADEP, 2013b). These levels surpass the single-largest industrial source of NO_x pollution in the 11-county northeast region, a coal-fired power plant in Northampton County that emitted 2,000 tons in 2011 (Legere, 2013).

2.2.3 Related Literature on Health and Shale Gas Development

Most of the studies to date that address potential health impacts of shale gas development measure pollutants at drilling sites or in drilling fluids and then identify the health implications based upon expected exposure to these chemicals. Colborn et al. (2011) find that more than 75% of the chemicals could affect the skin, eyes, and other sensory organs, and the respiratory and gastrointestinal systems. Chronic exposure is particularly concerning because approximately 40-50% could affect the brain/nervous system, immune and cardiovascular systems, and the kidneys; 37% could affect the endocrine system; and 25% could cause cancer and mutations. These may have long-term health effects that are not immediately expressed after a well is completed.

McKenzie et al. (2012) focuses on the health risk of air emissions from well pads in Colorado. The study collected emissions measurements in Garfield County and then estimated chronic and sub-chronic non-cancer indices and cancer risks from exposure to the measured emissions for residences less than 1/2 mile and more than 1/2 mile from wells. The study determined that the cancer risks within 1/2 mile of a well are 10 in a million and 6 in a million for those residences greater than 1/2 mile from a well. Benzene was the major contributor to the risk. These results indicate that health effects from air emissions from shale gas development warrant further study and prospective studies should focus on the health effects associated with air pollution. The authors replicated the findings from Garfield County in Battlement Mesa, CO and determined that there are 8 major areas of public health concern: water contamination, truck traffic, health effects from air emissions, noise and light pollution, strain on health care systems, accidents and malfunctions, psychosocial stress from community changes and housing value depression (Witter et al., 2013).

Bamberger and Oswald (2012) are the first peer-reviewed study to link human and animal health with natural gas development. Their study is supporting evidence of the need for further scientific studies addressing the potential health impacts caused by shale gas extraction practices. The authors interviewed 24 case study participants who are animal owners and live near gas drilling development around the country. Although their study is not an epidemiological analysis, nor is it a study that identifies specific chemical exposures related to shale gas development, it provides evidence that there are health risks present in natural gas development. Their study illustrates the potential impacts on animals by reporting on numerous cases of sudden death of cows, dogs, poultry, birds, goats, amphibians and fish. Their study also indicates that there are many common health problems reported in humans, such as upper respiratory, dermatological, neurological, and gastrointestinal health impacts.

The few studies focused on the air quality and health of people in Dish, Texas have yielded mixed results.[15] For example, the Texas Department of State Health Services (DSHS) conducted biological testing for 28 residents to determine levels of VOCs in their blood and found that the levels in the blood were similar to the US population (DSHS, 2010). VOCs have a half-life of about 4 hours in some cases and so determining exposures and prolonged exposures is difficult to determine with a single test. While another study, surveying 31 residents, found that 61 percent of the health impacts self-reported by the residents are known health effects of the VOCs detected in the air in 2009 (Subra, 2009; WEE, 2009).

2.3 Data

My analysis is based upon a data set acquired from the Pennsylvania Department of Environmental Protection (PA DEP) that contains GIS information for all of the wells drilled in the state of Pennsylvania since 2000 and define whether it is a Marcellus shale well. In total, the analysis uses 2,459 natural gas wells completed between 2006 and 2010. For the analysis that follows, the spud date (date when the drilling rig begins drilling the well) is used as the temporal identification of treatment. In addition to the existing gas well data, this study also makes use of the permit data on the PA DEP website. This allows for the identification of permits that do not become a well during the sample time

[15]These studies are not peer-reviewed, but are indicative of the current controversy regarding health and environmental effects of shale gas development.

frame. This information is used to define a potential control group for those infants born to residences close to existing gas wells. The assumption being that these residences are a potential counterfactual group: those who have the potential to live close to a gas well in the future, but have not yet had a well drilled as of the timing of the data collection.

My second source of data comes from restricted-access vital statistics natality and mortality data from Pennsylvania for the years 2003 to 2010. The restricted-access version of these birth certificate records contain residential addresses geocoded to latitude and longitude and unique identifiers for the mother, father and infant. This precision is essential to my identification strategy because the consequences of drilling are highly localized (Sage Environmental Consulting, 2011; Muehlenbachs et al., 2014). The vital statistics contain important maternal characteristics such as race, education, age, marital status, WIC status, insurance type, and whether the mother smoked during her pregnancy. In the empirical analyses that follow, I control explicitly for these, as well as month of birth, year of birth, the interaction, and gender of the child.[16] I exclude multiple births in all analyses because plural births are more likely to have poor health at birth independent of exposures to environmental pollution.

I focus on low birth weight (LBW) and term birth weight as the primary outcomes of interest. Low birth weight, defined as birth weight less than 2500 grams, is commonly used as a key indicator of infant health and has been shown to predict adult health and well-being.[17] Low birth weight is a latent variable as defined and so I also present the

[16] I also test whether drilling activity has affected these characteristics directly by changing fertility and/or the composition of families living near shale gas development and I find few economically significant changes.

[17] Oreopoulos et al. (2008) use twin and sibling fixed effects models on data from Manitoba, Canada that follows births through 18 years of age to show that birth weight (and other infant health measures) has a significant effect on both mortality within one year and mortality up to age 17. They also find that birth weight is a strong predictor of educational and labor force outcomes, such as high school completion and welfare take-up and length. These findings are similar to those of Black et al. (2007) who use data from Norway and find that birth weight has a significant effect on earnings, education, height and IQ at age 18. Johnson and Schoeni (2011) use national data from the US and find that

continuous measure of term birth weight, defined as birth weight for infants who reach full term at 37 weeks gestation. Other birth outcomes that I examine include the continuous measure of birth weight, gestation (measured in weeks), premature birth (defined as gestation length less than 37 weeks), small for gestational age (SGA; defined as 10th percentile of weight distribution for the gestational week of birth), congenital anomalies, and infant mortality (death in the first year).[18] Another potential measure of health at birth is the 5 minute American Pediatric Gross Assessment Record (APGAR) score.[19] I use an indicator for whether the APGAR score is less than 8 to predict an increase in the need for respiratory support. Each of these outcomes has been previously examined in both the epidemiological and economics literature (e.g., Currie and Neidell (2005); Currie et al. (2011); Mattison et al. (2003); Glinianaia et al. (2004); Knittel et al. (2011); Currie et al. (2009); Currie and Walker (2011); Currie et al. (2013a)). Following Currie et al. (2013a), I also construct a single standardized measure to address examining multiple outcomes and multiple hypothesis tests (Kling et al., 2007).[20]

The third data source utilized in this research is a shape file containing the boundaries of public water service areas (PWSA) provided by the Pennsylvania Geospatial Data

low birth weight increases the probability of dropping out of high school by one-third, lowers labor force participation by 5 percentage points, and reduces earnings by almost 15 percent. More recently, Figlio et al. (2013) use linked birth and schooling records in Florida and find that birth weight has a significant impact on schooling outcomes for twin births.

[18]Small for gestational age (SGA) is used to determine the immediate health care needs of the infant and is used increasingly to predict long-term adverse health outcomes and potential exposure to environmental pollution (Callaghan and Dietz, 2010). This paper uses the World Health Organization weight percentiles calculator (WHO, 2011) which follows the calculations recommended by Mikolajczyk et al. (2011).

[19]The physician rates the infant a 0, 1, or 2 on each of 5 dimensions (heart rate, breathing effort, muscle tone, reflex initiability, and color), and then sum the scores, giving an APGAR score of 0-10, where 10 is best. This discrete measure is highly correlated (when the score is low) with the need for respiration support at birth (Almond et al., 2005).

[20]I first convert each birth measure so that an increase is "adverse" and then standardize the measure to a mean of zero and standard deviation of 1. I then construct the summary measure by taking the mean over the standardized outcomes, weighting them equally.

Clearinghouse (PADEP, 2013a). Using a geospatial merge, I link the mother address to the service area boundaries and then define whether the mother's residence uses piped public water or private (ground) well water. Additionally, I define distance from the boundary of the PWSA to explore birth outcomes amongst residences very close to the boundary to reduce confounding relationships linked to different drinking water sources (Muehlenbachs et al., 2014).

Table 2.1 provides summary statistics for the universe of births in Pennsylvania from 2003-2010. The first column reports characteristics of all births and the second column reports characteristics of births for mothers' residences within 2.5 km of where a shale gas well has been drilled or will be drilled. The localized data I use in this analysis is actually quite similar to the characteristics of the rest of the state.[21] Column (3) provides a decomposition of birth weight of residences within 2.5 km of a well to gauge the importance of the various observable mother characteristics. The regression also includes month of birth, year of birth, and county of birth dummies to account for any secular time trend. These control variables are included in all my subsequent regression analysis, but, for simplicity, I do not report these coefficients in the tables below.

Table 2.2 provides summary statistics for the primary difference-in-difference (DD) analysis sample to assess how selective my main estimation sample is. In the analysis that follows, the sample is restricted to those mothers' residences within 2.5 km of a gas well or permit (future well) and I compare residences before and after drilling. The cross-sectional differences in sample means for characteristics of birth and mother's demographic characteristics are reported in Table 2.2. Most of the statistically significant differences between these two samples are arguably not very economically important. Mothers with infants born after drilling are less likely to be over the age of 35, more likely

[21] Mothers who live close to shale gas development are less African American and Hispanic, slightly better off in terms of health outcomes, younger, better educated and more likely to be married at the time of birth compared with the state average. The mothers in the analysis sample are also more likely to smoke than the average for the state.

to receive WIC, and more likely to receive Medicaid, on average. However, when controlling for county time trends, Table 2.3 suggests no changes in these economic variables after shale gas development.

2.4 Empirical Strategy

Since air or water pollution are not randomly assigned, studies that attempt to compare health outcomes for populations exposed to pollution may not adequately control for confounding determinants of health. In the absence of a randomized trial, I exploit the variation over time in the introduction of shale gas wells in Pennsylvania during 2003-2010. Combining gas well data and vital statistics allows the comparison of infant health outcomes of those living near a gas well and those living there before drilling began. Rather than compare aggregated areas, I know specific locations where shale gas drilling has taken place and the dates of when drilling began. The specific location data allow me to compare health at birth within very small areas in which mothers are likely to be more homogeneous in observable and unobservable characteristics than in normal aggregate comparisons.

Relying on cross-sectional variation alone, however, would be problematic if mother characteristics vary within the small radius of interest that are unobservable to the researcher. If, for example, the location of gas drilling occurs where the neighborhoods are already economically distressed, then the variation in health outcomes may reflect socioeconomic status, as opposed to living in close proximity to shale gas development. This is a constant concern in the literature that attempts to exploit variation in health at birth (see Currie and Walker (2011)). I therefore examine localized health at birth outcomes shortly before and after shale gas drilling. There is little guidance in the literature about how near a household must be to a gas well for exposure to affect birth outcomes. Currie et al. (2013a) characterize this relationship empirically using low birth weight and find that toxic emissions from toxic plants travel at least 1 mile.[22] I use 2.5 km as the primary distance of interest for the main specifications that follow. In Appendix Table A.2, I report different distances from the well head for the definition of treatment. I detect increases in low birth weight and decreases in term birth weight up to 3.5 km from the well head, an important contribution of this paper and of significant independent interest to the policy debate around shale gas development.

One important caveat is that, like all such studies, I can observe health at birth for only those babies that are born alive. Also, I can only observe births for those mothers who "choose" to get pregnant. If the composition of mothers "choosing" to get pregnant changes with the introduction of shale gas development, then the health that I observe may not be indicative of the average health of those living near wells in these neighborhoods.[23]

2.4.1 Graphical Evidence

If living close to a drilled well has a negative impact on infant health at birth, we should see average prevalence of low birth weight for mother's residences in close proximity to wells increase subsequent to when drilling begins. Moreover, we should observe larger impacts for homes closest to drilling activity. Figure 2.1 shows the low birth weight (LBW) gradient of distance to closest well before and after drilling. LBW prevalence is on

[22]There are some other clues in the current literature regarding shale gas development: McKenzie et al. (2012) predict health effects more than a half mile from the well head, Colborn et al. (2012) detect air pollution at high levels at 1.1 km of the well head, and using ambient air pollution modeling, Sage Environmental Consulting (2011) recommend distances from schools and hospitals of more than a mile from the well head.

[23]An examination of fertility over time suggests a consistent number of births within 2.5 km of the well head. Muehlenbachs et al. (2014) do not find any changes in neighborhood composition using Census data at the tract level from 2000-2012 in Pennsylvania.

average higher for those residences close to drilled wells, compared with those who are close to permitted wells. This persists out to almost 5 km. The notion that the reduction in birth weight within 2.5 km of a well reflects the causal impact of drilling activity would be supported if the decline coincides with when drilling begins and does not reflect a preexisting downward trend in birth weights. Figure 2.3 shows the LBW gradient of time with respect to when drilling begins. This gradient is measured for births 500 days before and after drilling for residences within 5 km of a well. If the low birth weight increase showed in figure 2.1 reflected a preexisting trend, we would see a consistent upward trend over this time period prior to when drilling begins. Instead, I find a fairly sharp increase in low birth weight coincident with the spud date (defined as time=0) for residences within 2.5 km of a shale gas well. In contrast, the average low birth weight for residences at greater distances (but less than 5 km) from a well did not increase after drilling began. It is therefore plausible that the two groups would have had a similar trend in low birth weight prevalence over time in the absence of shale gas development.

In contrast, figure 2.2 shows the premature birth gradient of distance to closest well before and after drilling. Here, we do not see a clear trend in premature birth over distance (this result is confirmed in the regression analyses that follow; there is no effect of drilling on premature birth within 2.5 km of a well). Figure 2.4 shows the trend in premature birth. Again, as was suggested by Figure 2.2, there does not appear to be a clear relationship between drilling and premature birth.

2.4.2 Statistical Estimation Framework

I proceed by estimating models informed by the graphical evidence to investigate the effects of proximity to gas wells on infant health. First, I use the cross-sectional difference estimator to check for pre-existing differences in the characteristics of mothers whose residences are located within 2.5 km of a shale gas well. Given the similarity, I then use a difference-in-differences model –in which mothers living within 2.5 km from a well head before drilling are used as a control for those exposed after drilling began– to estimate the impact of exposure to shale gas development on birth outcomes.

The cross-sectional difference specification takes the following form:

$$Outcome_i = \beta_0 + \beta_1 D_i^{2.5km} + \alpha_i + \epsilon_i \tag{2.1}$$

$Outcome_i$ is a function of a measure of distance from the resource well, a random error term (allowing for specific correlation in health by county), α_i, a county, month and year specific effect. $D_i^{2.5km}$ is an indicator variable set to one if the mother's residence is within 2.5 km of a well. I present these results within 5 and 15 km of any well, with and without maternal characteristics. To examine variation in other mother characteristics, I substitute those characteristics for $Outcome_i$ as the dependent variable.

The difference-in-difference specification adds an indicator variable for if the birth occurs after the closest well was spudded ($Post_i$) and the interaction of this indicator with the distance indicator ($D_i^{2.5km}$). Thus, the counterfactual change in infant health for mother's residences close to a shale gas well is estimated using births prior to drilling at the same distance from the well head:

$$\begin{aligned} Outcome_i = \delta_0 + \delta_1 X_i + \delta_0 D_i^{2.5km} + \delta_1 Post_i \\ + \delta_2 D_i^{2.5km} * Post_i + \alpha_i + \chi_i + \epsilon_i \end{aligned} \tag{2.2}$$

α_i are birth month and year fixed effects, and χ_i are county fixed effects. X_i are mother and birth characteristics.

The estimated impact of shale gas drilling on infant health is given by the term δ_2

and is the difference-in-differences estimator. χ_i is designed to capture any unobserved time-invariant characteristics of each county in the sample. α_i are included to address seasonal and secular time trends. The standard errors in these models are clustered at the mother's residence county. The vector X_i contains mother and child characteristics including indicators for whether the mother is African American, Hispanic, four mother education categories (less than high school (left out category), high school, some college, and college or more), mother age categories (teen mom (left out category), 19-24, 25-34 and 35+), indicators for smoking during pregnancy, an indicator for receipt of Women, Infants, and Children (WIC), three health care payment method categories (Medicaid, private insurance, and self-pay), mother's marital status and an indicator for sex of the child.

The main model, equation (2.2), is estimated using a comparison group that is restricted to those infants born to residences within the specified distance of a permit or future gas well. For example, the 2.5 km comparison group is composed of infants whose mother's residence is within 2.5 km of a permit or future drilled well. The 2.5 km affected group is thus defined as those infants that are born after a shale gas well is completed within 2.5 km of their mother's residence. This identification strategy assumes that infants born within a similar distance to a permit that is a potential future well would face similar ex ante conditions as those born close to a permit that did become a well during the sample and that the birth outcomes are similar on average. Infants born to mothers who reside close to potential wells are likely to be the most similar comparison group when it comes to family, geological formation and community characteristics. The decision for which permits become a well is arguably exogenous to the families in these locations. This should account for both observable characteristics, as well as unobservable characteristics, such as economic factors that promote gas drilling in a community and the unobserved geology of the shale underneath these communities.

The main model is also estimated with the sample of mothers who have multiple singleton births from 2003-2010. Using those who have ever resided within 2.5 km of a well or future well, I also estimate a maternal fixed effects model for the outcomes of interest. Estimating equation (2.2) with a dummy for each unique mother on the sample with singleton siblings addresses concerns about endogenous mother-specific time-invariant factors that may influence birth outcomes (e.g. propensity to move, propensity to engage in risky behaviors, or differential fertility in response to drilling activity). This also allows me to test whether drilling induces families to move.

Ground water contamination from the process of hydraulic fracturing has received the most media attention as a pathway for adverse public health effects. This concern is discussed in detail in Section 2.2.2. Following Muehlenbachs et al. (2014), I test whether there are heterogeneous effects of shale gas development by water source. The full model takes the form:

$$\begin{aligned} Outcome_i = \delta_0 + \delta_1 X_i + \delta_0 D_i^{2.5km} + \delta_1 Post_i + \delta_3 PWSA_i \\ + \delta_2 D_i^{2.5km} * Post_i + \delta_4 D_i^{2.5km} * PWSA_i + \delta_5 PWSA_i * Post_i \\ + \delta_6 D_i^{2.5km} * Post_i * PWSA_i + \alpha_i + \chi_i + \epsilon_i \end{aligned} \tag{2.3}$$

where the other controls are the same as the main equation (2.2). δ_6 is the triple-difference estimator of the impact of proximity to a well after drilling for homes on public water. PWSA is an indicator equal to one if the maternal residence receives piped public water from a public water service area (PWSA) and equal to zero if the maternal residence uses private well water.

2.5 Estimation Results

2.5.1 Differences in Characteristics of Mothers Close to a Well

I formally test whether there are any preexisting trends in adverse birth outcomes or characteristics in these communities prior to drilling. First, I limit the sample to births that took place before any drilling began and estimate equation (2.1) using residences within 5 km from future gas wells. In Table 2.3: Panel A, I compare those within 2.5 km to those 2.5-5 km from a future gas well and find little evidence of any preexisting differences in either health at birth or mother characteristics that would be indicative of worse health trends in these communities prior to drilling. Although there are some statistically significant differences, these communities boast heavier babies. Mothers who live within 2.5 km from a permit appear to have less education than those who live 2.5-5 km from a permit and they are also more likely to be born in Pennsylvania. Despite these significant differences, there doesn't appear to be any systematic adverse health trend prior to drilling that would threaten the conclusions that follow.

To further test the validity of my research design, I also estimate equation (2.2) and use the difference-in-difference estimator to see if there are any changes in mother characteristics after drilling began. In Table 2.3: Panel B, only one maternal characteristic shows a significant change with drilling: mothers observed after drilling are more educated than those observed prior to drilling. Increased college completions amongst mothers would suggest improvements in infant health in these communities, rather than adverse health effects. However, this does suggest some selection and so I include these and other controls in all the subsequent results.[24]

[24]The time frame of interest is during the onset of the Great Recession. It may indicate that the opportunity cost of going to college, or becoming a mother, has reduced and so more educated mothers are having children. Other research has linked recessions to improved infant health outcomes, so it is unlikely to be the driver of impacts reported in

2.5.2 The Impact of Shale Gas Development on Low and Term Birth Weight

To more fully examine pre-drilling trends in birth outcomes, I first present estimates of equation (2.1) in columns (1) and (3) of Table 2.4, including birth month, year and county fixed effects, but no other control variables. In columns (2) and (4), I present estimates that include maternal characteristics. A reliable indication that the estimation strategy is sound occurs when these two estimates do not differ in magnitude or significance from each other. The estimates β_1 from this specification are simply a measure of the average difference in low (term) birth weight for residences within 2.5 km of a future gas well compared to residences within 5 km of a future well. Including maternal controls has little impact on the estimates. Living closer to a future drilling site is associated with a 0.2 percentage point reduction in low birth weight and a 15 gram increase in term birth weight, on average. These differences in low birth weight and term birth weight are suggestive of heavier infants and shows that birth outcomes may have been better off prior to drilling in the closest proximity to future drilling sites.[25]

Table 2.4 shows the main results from estimating equation (2.2). Distance to a (future) well is held fixed at 2.5 km for these models. Each coefficient represents an estimate of δ_2 –my difference-in-difference estimator– from a separate regression. Columns (5) and (7) show a model that controls only for month and year of birth and county fixed effects. Adding controls for observable characteristics of the mother should only reduce the sampling variance while leaving the coefficient estimates qualitatively unchanged. Columns (6) and (8) add maternal characteristics and show that controlling for maternal

the next section (Chay and Greenstone, 2003; Dehejia and Lleras-Muney, 2004).

[25]To make sure that this is not driven by the comparison group, I also estimate equation (2.1) with residences within 15 km of a future well. These differences are similarly suggestive of better birth outcomes closest to future drilling sites prior to drilling (Appendix Table A.1).

characteristics has little effect on the estimated coefficients. I find a statistically significant increase in low birth weight of 1.36 percentage points and a reduction in term birth weight of 49.58 grams, on average. Thus, mothers who give birth after drilling are more likely to have reduced weight babies. This difference is suggestive of an overall increase in low birth weight of 25 percent (base of 5.5 percent) and a decrease in term birth weight of 1.5 percent (base of 3418 grams), on average.[26] The results are qualitatively similar when I estimate equation (2.2) for other distances up to 4 km from a gas well or permit (See Appendix Table A.2).

2.5.3 The Impact of Shale Gas Development on Alternative Measures of Health

Table 2.5 presents similar estimates to Table 2.4 for changes in birth weight, 5 minute APGAR scores less than 8, gestation (weeks), premature birth, small for gestational age (SGA), congenital anomaly and infant death. As before, each column presents estimates from a separate regression, comparing outcomes before and after drilling at 2.5 km from a well head. The first column of each measure is estimated without maternal characteristics and the second column of each measure includes maternal characteristics. Again, controlling for maternal characteristics does not have an appreciable effect on the estimates. Looking across all health at birth measures, these estimates are consistent with shale gas development being detrimental to infant health. The introduction of shale gas development reduced birth weight by 46.6 grams (1.4 percent reduction), which is consistent with the findings for term birth weight. Five minute APGAR scores were also affected by drilling; drilling increased scores less than 8 by 2.51 percentage points or an overall increase of 26 percent. Small for gestational age (SGA), a strong indicator of in-

[26] Overall prevalence is calculated as follows: 0.0136/0.055=24.7 percent low birth weight and 49.6/3418 = 1.5 percent reduction in term birth weight.

trauterine growth restriction (IUGR), increased by 1.81 percentage points or an increase of 18 percent from the mean. Perhaps surprisingly, given that low birth weight is often correlated with premature birth, gestation and premature birth show no difference with the introduction of shale gas development. Congenital anomaly and infant death are not individually statistically significant from zero, but these outcomes are quite rare and differences are not likely to be detected with the size of my sample.[27]

Following Currie et al. (2013a), I address the issue of precision using a summary index measure of infant health. A drilled shale gas well has a small and statistically significant effect on the summary index, increasing the probability of an adverse health at birth outcome by 0.026 standard deviations. This result is consistent with the finding that living within 1 mile of an operating toxic plant increased the probability of a poor health outcome by 0.016-0.017 standard deviations (Currie et al., 2013a).

2.5.4 The Impact of Shale Gas on Infant Health by Water Source

Piped water is regulated by the Clean Drinking Water Act and monitored by the EPA, whereas ground water is the responsibility of the residential owner to test for contaminants.[28] Table 2.7 presents the results for equation (2.3).[29] This formally tests whether there are differences between water source in the infant health outcomes detected in the main results (δ_6 on the interaction $D_i^{2.5km} * Post_i * PWSA_i$). For example, for low birth weight, ground water homes had an increase in low birth weight of 0.425 percentage points and public piped water homes had an increase in low birth weight of 0.556 per-

[27]Currie and Neidell (2005) and Currie et al. (2009) used samples greater than 125,000 to detect changes in infant mortality.

[28]Water testing can be costly and prohibitive for some families.

[29]I report the coefficients required to calculate two effects: the effect of shale gas development for ground water homes versus piped public water homes 2.5 km of a well post-drilling. Full results available upon request.

centage points post-drilling within 2.5 km of a well. Similarly, public water homes had reduced term birth weight of 32.11 grams, while ground water homes had reduced term birth weight of 19.69 grams, on average. Despite some differences in magnitude, the differences between the estimates are not statistically significant and suggest that the exposure mechanism is likely air pollution or increased economic activity in these communities (e.g. increased noise, stress from community change).[30]

2.5.5 Maternal Fixed Effects

My estimation strategy hinges on the relative similarity between mothers residing within 2.5 km of a well to mothers residing within 2.5 km of a permit or future well. One potential threat to my identification strategy is that selection into locations near drilling areas after drilling begins is correlated with other maternal behaviors that are detrimental to infant health (e.g. smoking, drinking) and that these behaviors are the drivers of the adverse health effects detected. To test this, I estimate a maternal fixed effects model, which accounts for mother-specific time-invariant unobservable factors, and is presented in Table 2.6. The results suggest a reduction in term birth weight of close to 20 grams on average and an increase in low birth weight of 1.51 percentage points. These are qualitatively similar to the main results of the paper but are not precisely estimated. The main model is thus robust to unobservable mother-specific time-invariant responses to shale

[30] Appendix Table A.4 provides the cross-sectional demographic characteristics for the analysis sample on ground versus piped water. Those on piped water are more likely to have worse birth outcomes in the cross-section, which may be due to proximity to urban/semi-urban locations. Following Muehlenbachs et al. (2014), I also test whether there are differences within a tight bandwidth of 1 km on either side of the public water boundary. This assumes that ground water sourced homes near the boundary are more similar to piped homes in observable and unobservable characteristics than those on ground water farther from the boundary. This subsample confirms that there are no differences in shale gas impacts across water sources (Muehlenbachs et al. (2014) found differences only in the subsample for housing prices). Estimation of equation (2.2) with the sub sample within 1 km on either side of the public water boundary yields similar results as those reported in Table 2.4. Results available upon request.

gas development.[31]

Table 2.8 shows estimates of maternal mobility for the same sample used in the maternal fixed effects models. The first column predicts the likelihood that a mother moved (changed residential location) between pregnancies. The coefficient suggests that moving increased by 2.2 percentage points after drilling, although this is not statistically significant. The next six columns report the birth outcomes for the mothers who moved and the mothers who do not move. Despite some potential increased mobility of these mothers, the results are qualitatively similar for those who stay as those who move and indicate that the main results are not driven by maternal mobility.[32]

2.5.6 Robustness Checks

Another difference-in-difference model commonly used in the environmental health literature is to compare observed health close to a pollution source versus slightly further away. The most recent of these studies is (Currie and Walker, 2011); the authors compared mothers within 2 km of a toll plaza to mothers who are 2-10 km from a toll plaza, before and after the adoption of E-Z Pass in Pennsylvania and New Jersey.[33] In

[31] The sample of mothers with multiple singleton births, with residence in the radius of interest, is less than 50 percent of the main sample, and there is limited within variation. The mother fixed effects model addresses time-invariant, family-specific measurement error. However, these models do not account for maternal learning or endogenous mobility. Additionally, the sample of mothers who have multiple singleton births are somewhat different from the analysis sample in the main results: they have heavier babies, are more likely to be high school drop outs and less likely to be college educated, less likely to be teen mothers, more likely to be Black and more likely to receive medicaid. An instrumental variables approach could address the remaining endogeneity, however, I do not know of an instrument that would meet the exclusion condition in this context. Descriptive statistics available upon request.

[32] A more detailed discussion of mobility is presented in Appendix Section A.1.

[33] Chapter 3 also uses this research design to explore the impacts of oil and gas development in Colorado, comparing 1 km to 1-5 km away from the well head, before and after drilling.

Appendix Table A.1, I present results utilizing a similar model as a robustness check for using permitted/future wells as the comparison group. Here, the difference-in-difference model compares residences close to a well (within 2.5 km) and residences a little further away (2.5-15km), before and after drilling. The point estimates are somewhat smaller, but still suggestive of a statistically significant increase in low birth weight and decrease in term birth weight, on average. Using 2.5-15 km as the comparison group provides a lower-bound estimate; shale gas development increases the overall prevalence of low birth weight by 12.5 percent and reduces term birth weight by 0.6 percent, on average.[34]

Table 2.9 contains estimates of robustness checks for four measures of infant health: low birth weight, term birth weight, birth weight and small for gestational age. Each coefficient represents an estimate of δ_2 from a separate regression for various subgroups and additional controls. The first panel shows the effect of restricting the sample to infants born within 2 years (before and after) of the spud date for the closest well. This specification is designed to address any possible concerns about unequal prior and post observation periods for each location or concerns about unobserved and differential sorting in the mothers living close to drilled versus permitted wells. The point estimates are somewhat smaller, but qualitatively similar to the estimates in Tables 2.4 and 2.5. Table 2.9: Panel B shows the results using the sample of births from 2008 to 2010, when most of the shale gas development took place during the sample frame. This point estimate is slightly larger for low birth weight (LBW) and small for gestational age (SGA) indicating a 1.89 and a 2.51 percentage point increase in LBW and SGA, respectively. Also a slightly larger point estimate, column (3) suggests that birth weight is reduced by 54.8

[34]Depending on the scale of shale gas development, it is possible that other aspects of drilling activity will influence infant health within 15 km of a well and could explain these smaller estimates. For example, communities with shale gas development are exposed to increased truck traffic, pipelines, water storage, compressor stations and general increased localized economic activity. These community level effects are less likely to influence the estimates in the main results of the paper that use permitted/future wells as the comparison group.

grams on average and is statistically significant. Column (2) suggests a reduction in term birth weight of 31.5 grams, but is no longer statistically significant. Panel C reports the results from adding the continuous distance to the closest well, as well as the number of wells drilled within 5 km of the maternal residence. Again, the point estimates are very similar to those reported in Tables 2.4 and 2.5.

An important issue to explore is whether the effects of exposure to shale gas drilling are the same for different subgroups of the population. Some groups, such as high school dropouts, African American mothers and smokers, may face differential risks from similar levels of pollution exposure. To assess any heterogeneous impacts of shale gas development across different demographic groups, the next three panels of Table 2.9 highlight estimates from these important subgroups. The sample of African American mothers is very small, making up just 3% of the sample, but the coefficient estimates suggest larger impacts albeit not statistically significant. Currie et al. (2009) and Currie and Walker (2011) found larger effects of pollution for mothers who were smoking. Within 2.5 km of a drilled or future well, the sample of smokers has a point estimate of 1.94, however, smokers in the population are more likely to have low birth weight babies at baseline and so this does not suggest a differential effect on the incidence of low birth weight for smokers. And the coefficient is not statistically significant (p-value=0.16). However, term birth weight is reduced by 62.3 grams and is statistically significant and suggests a larger effect on average term birth weight for infants born to smokers (1.9 percent reduction). The effects for high school dropouts are much larger (Panel F) and suggest that maternal exposure to shale gas development for high school dropouts increases low birth weight by 4.8 percentage points, reduces term birth weight by almost 80 grams, and reduces continuous birth weight by over 100 grams, on average. This result may be indicative of less avoidance behaviors amongst the least educated mothers surrounding drilling locations. Additional subgroup analyses are presented in Appendix Section A.3.

2.5.7 Falsification Tests

My analysis shows little evidence of any preexisting differences in communities located close to drilled wells relative to communities close to permits or future wells. It is theoretically possible that the increase in low birth weight after drilling is driven by differential trends in fertility or migration post-drilling amongst mothers who do not have multiple births during the sample. I investigate this possibility by estimating equation (4.4.3) using permit dates to define exposure, instead of spud dates. I also create a placebo test using a random date for the closest well. In these specifications, I find no evidence of a spurious effect, although the coefficient on term birth weight suggests that there may be a reduction in average term birth weights after the permit date but this result is fairly small and not statistically significant (Table 2.10, column (5)).[35]

2.6 Discussion and Interpretation

There are five main findings in this paper. First, my results suggest that shale gas development can have adverse effects on the health of people living nearby, namely that of prenatal infants. Babies born of mothers who lived within 2.5 km of a gas well during pregnancy had lower birth weights on average after drilling than prior to drilling. Shale gas development increased the incidence of low birth weight and small for gestational age in the vicinity of a shale gas well by 25 percent and 18 percent, respectively. Furthermore, term birth weight and birth weight were decreased by 49.6 grams (1.5 percent) and 46.6 grams (1.4 percent) on average, respectively, and the prevalence of APGAR scores less than 8 increased by 26 percent. Utilizing a health index, I find that drilling increased the probability of an adverse health at birth outcome by 0.026 standard deviations of the

[35]In some cases, land clearing and well pad preparation will take place after permit date.

index. While these impacts are remarkably large, they are biologically plausible given the correlations between air pollution (or maternal stress) and birth outcomes found in previous studies. For example, Zahran et al. (2012) found exposure to benzene reduced birth weight by 16.5 grams and increased the odds of a very low birth weight event by a multiplicative factor, and Slama et al. (2009) found that exposure to benzene reduced birth weight by 77 grams. For context, Almond et al. (2005) found that smoking reduces a child's birth weight by about 202 grams. Given the wealth of studies that identify a causal link between birth weights and long-run outcomes, these impacts are likely to persist throughout these children's lives.

Second, while there is some weakly suggestive evidence that mothers may be more likely to move after drilling, there does not appear to be any evidence that higher SES mothers are systematically more likely to move in response to drilling activity. I cannot rule out moving as a form of avoidance behavior, which could mask the costs of drilling to communities where it occurs if those most affected move away. Using a mother fixed effects model, I find qualitatively similar results and I do not find differential effects for those who stay versus those who move, which provides evidence that the research design is robust to changes in maternal mobility, fertility or behavior in response to drilling activity.

Third, effects of gas drilling are larger for lower SES children. There is prior evidence that in some cases this is explained by the fact that lower SES women take fewer measures to avoid pollution. I do not, however, detect heterogeneous responses as measured by moving. As previously mentioned, early shocks to a child's health can persist for many years, hence if poorer families are unable to mitigate the risks of drilling activity their children's health development is likely to suffer, which is reflected in literature that finds pollution to be one potential mechanism by which SES affects health (Neidell, 2004).

Fourth, using public water service areas to define maternal residences that receive piped public water versus maternal residences that use well (ground) water, I do not find differences in adverse birth outcomes between these two groups. This is suggestive evidence that the mechanism is not through the exposure pathway of water.[36]

Fifth, though exact mechanisms are difficult to ascertain with the data currently available, the increase in small for gestational age and low birth weight without a symmetric increase in premature birth indicates that infants born to mothers exposed to drilling are coming to full term, but are small. Thus, exposures to drilling activity are suggestive of intrauterine growth restriction (<10th percentile of birth weight for gestational age), which has not been definitively linked in the literature to particulates, but instead indicative of high levels of polycyclic aromatic hydrocarbons (Glinianaia et al., 2004; Bobak, 2000; Sram et al., 2005). Low birth weight, in contrast, has been linked to many of the measured air pollutants associated with gas drilling and is indicative of exposures to benzene, particulates, SO_2, NO_x, and VOCs (amongst others). Despite emissions from shale gas development making up a small percentage of the total emissions measured in the entire state of Pennsylvania, shale gas development can be a source of substantial aggregate local pollution in rural areas that do not have established air pollution sources. These results suggest that requiring air pollution monitoring of drilling sites could assist researchers and public health officials in efforts to ascertain exposure pathways for residents living nearby and inform policies to mitigate any risks that are likely to be very localized.

Cost Estimates

While the economic benefits of shale gas development are quantifiable, the public health benefits may be more difficult to assess. Improvements in public health that stem

[36]This does not rule out ground or surface water contamination caused by shale gas development; it, however, indicates that changes in reproductive health in these communities after shale gas development is driven by something other than water source.

from electricity sourced from natural gas instead of coal are likely to be substantial, but not uniformly distributed. This paper provides evidence that maternal exposure within at least 1.5 miles of shale gas extraction is detrimental to fetal development. A recent report from the Institute of Medicine estimates that the cost to society of low birth weight and premature infants is $51,600 per infant for the first year of health care costs (in 2005 dollars, Behrman and Butler (2007)). A different estimate in the same year found that each preterm/low birth weight baby incurs an average of $15,100 additional hospital costs in the first year of life (Russell et al., 2007). I use this lower bound for the following cost calculations. Each low birth weight infant is fifty percent more likely to require special education services and each special education child costs the state of Pennsylvania $10,404 in 2007 (Chaikind and Corman, 1991; Augenblick et al., 2007). Following Currie et al. (2013a), I use $76,800 as an estimate of the discounted life time wages lost from low birth weight status.[37] Combining hospital costs attributable to low birth weight ($15,100 in additional hospital costs), estimates for special education services ($5,200) and decreased earnings ($76,800), an arguably conservative estimate is $96,500 in added cost for each low birth weight child.[38]

Due to shale gas development occurring only recently in Pennsylvania, the number of infants observed close to existing wells before birth is quite small, or just under 2,500 infants. This translates to a cost of $4.1 million and accounts mostly for infants born after gas development in 2010. As a back-of-the envelope estimate, even if we assume that only the same number of infants were exposed in 2011, this translates to a cost of $8.2 million associated with 2 years of shale gas development in Pennsylvania. This is all the more likely to be a lower bound given that 2,618 additional wells were drilled in 2011 (PADEP, 2010a). Using the 2010 sample of permits as an example, 21,646 infants were born within 2.5 km of a permit or existing well. The estimates in this paper suggest that,

[37]See Currie et al. (2013a) for more details regarding this calculation.

[38]This figure excludes medical bills after the first year, parental lost earnings and other costs and is, hence, a lower bound estimate of costs.

if all of these permits were drilled prior to birth, we would expect to see 310 additional low birth weight infants, an increase that could be valued at $29.9 million.[39]

A recent assessment by The Wall Street Journal estimates that over 15 million Americans live within 1 mile of an oil or gas well drilled since 2000 in 11 of the 33 states where drilling is taking place (Gold and McGinty, 2013). Using a rough estimate that half of those people are women and forty percent of them are ages 18-44, there are more than 2.8 million American women with a well within a mile of their homes (Howden and Meyer, 2010). Using the current fertility rate of 64 per 1000 women in this age group nationally (Martin et al., 2012), there are over $170,000$ pregnant women within 1 mile of a well in these states. Using the estimates in this paper as a benchmark, oil and gas development in these communities could amount to over $2,000$ additional low birth weight infants each year. This amounts to a cost of more than $230 million each year in the 11 states assessed by Gold and McGinty (2013).

2.7 Conclusions

My study seeks to understand and quantify the impacts of shale gas development on infant health. The chemicals used during drilling, cleaning drill rigs and hydraulic fracturing are linked to birth defects, cancer and reduced lung function, but there is little guidance from the scientific literature about the magnitude, time horizon or likelihood of these effects. Additionally, recent studies have shown an increase in air pollution associated with drilling, but little research has been done to assess how far these air pollutants can travel.

[39] In contrast, each shale gas well costs a producer between $2-3 million to drill and with 2,459 gas wells in this analysis, that amounts to $4.9 billion in production costs (Hefley et al., 2011).

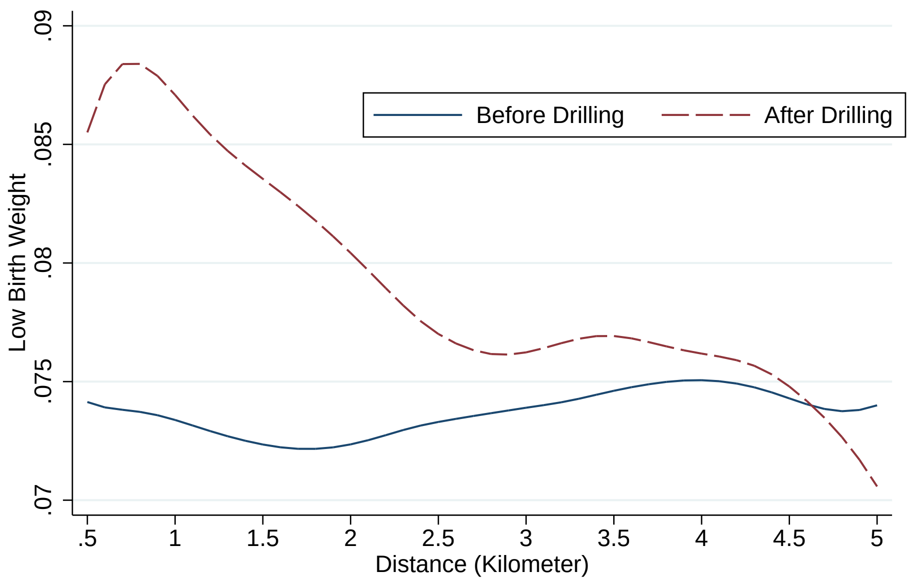
As a first step, I assembled a unique data set with the latitude and longitude of new mothers' residences and the locations of shale gas wells and permits in Pennsylvania. I examine the impacts of living in close proximity to shale gas development on low birth weight, term birth weight and other measures of infant health. This study is the first to examine health outcomes directly linked to shale gas development.

These results suggest that shale gas wells are associated with reduced average birth weight among infants born to mothers living within a 2.5 km radius from a shale gas well; this implies a monetized cost of $4.1 million. The impacts associated with shale gas studied in this paper are large but not implausible given the estimates found in the literature for air pollution impacts on low birth weight and term birth weight. I also find statistically significant increases in small for gestational age, the prevalence of five minute APGAR scores less than eight and decreases in birth weight on average. The strength of this approach is in exploiting a natural experiment that controls for unobservable characteristics and the results are robust across a variety of specifications, providing evidence on the credibility of the research design.

It is clear from these results that policies intended to mitigate the risks of shale gas development can have significant health benefits. I find detectable effects of shale gas development on low birth weight and term birth weight more than 3.5 km from the well head (more than 2 miles or over 11,000 ft). This finding is of significant independent interest and an important contribution of this paper. Current required set back distances (distance between well head and nearby residences, hospitals and schools) range from 300 ft to 800 ft across the 33 states where shale gas development is taking place. With detectable infant health effects up to 2 miles away, these set back distances may be deemed insufficient to protect human health. The impacts of shale gas development estimated in this paper are independent of drinking water source and suggest that the mechanism by which shale gas development adversely affects reproductive health is through the pathway of air pollution. This finding also adds impetus for regulators to increase regulations that reduce air pollution emissions from drilling operations and for industry actors to increase voluntary action to reduce air pollution emissions.

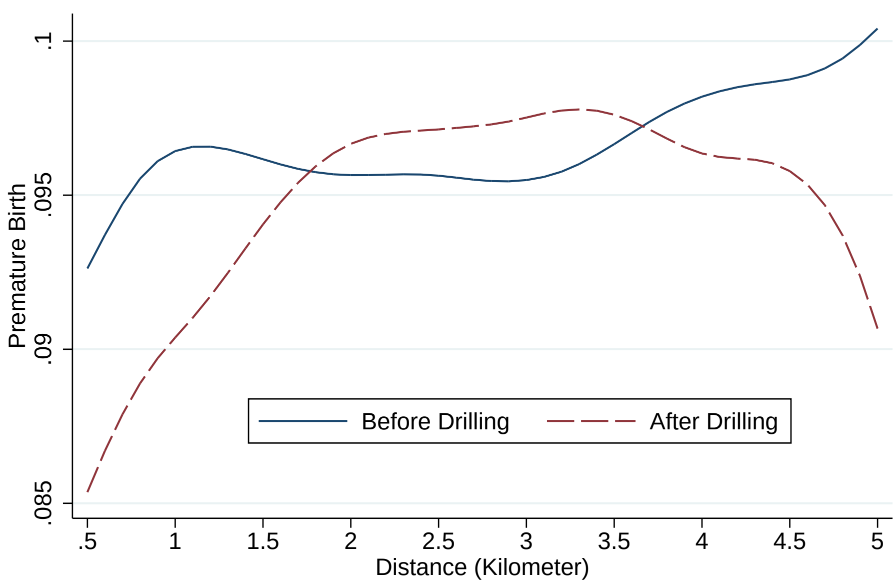
While the research design does not allow for causal claims regarding the precise mechanisms of the effects of shale gas development on infant health, related research informs us that there are many potential pathways of exposure. These findings then confirm that these pathways, and the nature and magnitude of their impacts, merit further investigation. In order to mitigate the potential risks, we need more guidance from scientific studies to show how far air emissions from gas operations are transported and/or the likelihood of surface and ground water contamination. Additionally, since I have focused on only the infant health effects of shale gas development, the total health effects of drilling exposure are likely to be much greater. Further research on the longer term health impacts of shale gas development on all members of our society –as well as the probable mechanisms and how best to mitigate them– is warranted.

Figure 2.1: Low Birth Weight Gradient of Distance from Closest Shale Gas Well



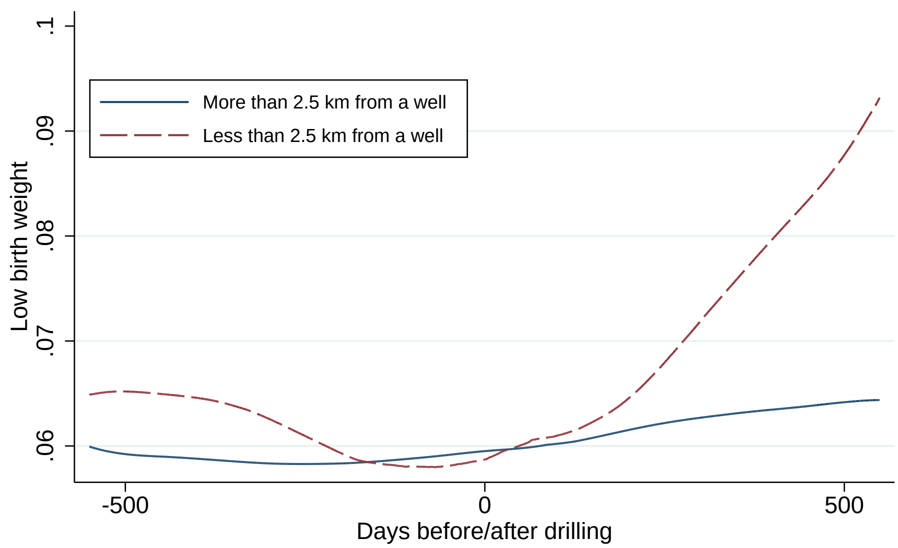
Results from local polynomial regressions (bandwidth=0.1 km) of low birth weight on distance from closest well's future/current location. Source: Author calculations from Pennsylvania Department of Health Vital Statistics.

Figure 2.2: Prematurity Gradient of Distance from Closest Shale Gas Well



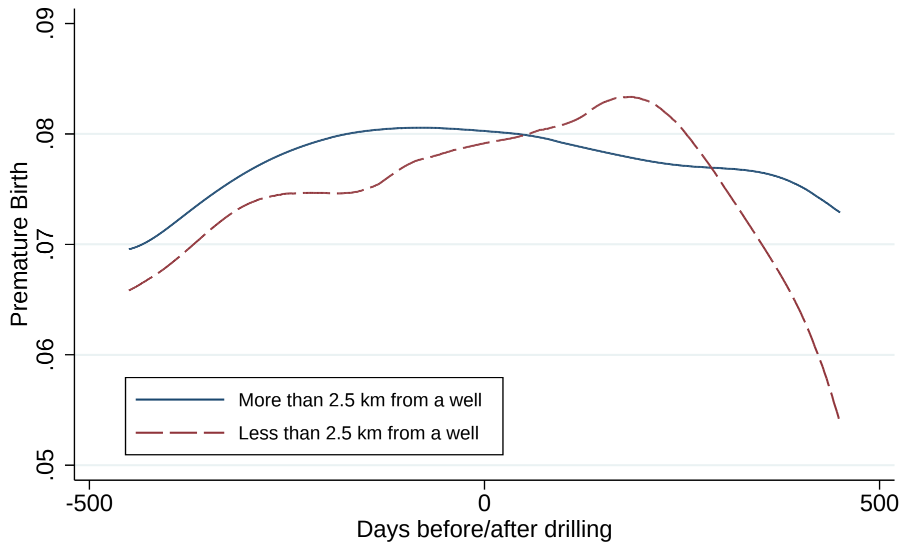
Results from local polynomial regressions (bandwidth=0.1 km) of premature birth on distance from closest well's future/current location. Source: Author calculations from Pennsylvania Department of Health Vital Statistics.

Figure 2.3: Low Birth Weight Trends Before and After Drilling



Results from local polynomial regressions (bandwidth=90) of low birth weight on days before/after spud date. Observations within 5 km of a well. Source: Author calculations from Pennsylvania Department of Health Vital Statistics.

Figure 2.4: Prematurity Trends Before and After Drilling



Results from local polynomial regressions (bandwidth=90) of premature birth on days before/after spud date. Observations within 5 km of a well. Source: Author calculations from Pennsylvania Department of Health Vital Statistics.

Table 2.1: Characteristics of Births in Pennsylvania, 2003-2010

	All Births	Residences within 2.5 km of well	
	Mean	Mean	Marginal effect in birth weight regression
Characteristics of birth			
Birth weight (grams)	3285.361	3309.93	
Term birth weight (grams)	3396.84	3404.62	
Gestation in weeks	38.554	38.567	
Premature	0.102	0.092	
Low birth weight (LBW)	0.083	0.071	
Small for gestational age (SGA)	0.116	0.107	
Female	0.49	0.49	
Mother's Characteristics			
Drop Out	0.162	0.111	
High School	0.269	0.295	36.03***
			(12.74)
Some college	0.26	0.299	55.18***
			(12.42)
College plus	0.302	0.291	75.53***
			(17.71)
Teen Mom	0.056	0.047	
Mom Aged 19-24	0.262	0.266	-14.41
			(17.78)
Mom Aged 25-34	0.529	0.548	-3.928
			(16.35)
Mom Aged 35 and older	0.153	0.139	-0.0640
			(19.34)
Mom Black	0.157	0.025	-117.9***
			(12.29)
Mom Hispanic	0.091	0.011	70.44
			(52.58)
Married at time of birth	0.578	0.635	56.98***
			(9.674)
Mom Smoked While Pregnant	0.225	0.298	-161.1***
			(6.783)
Received WIC	0.384	0.399	20.19**
			(7.724)
Medicaid	0.27	0.323	-44.76**
			(21.42)
Sample Size	1116978	22257	19582
R^2			0.053

Source: Author calculations from Pennsylvania Department of Health Vital Statistics. * p<0.10, ** p<0.05, *** p<0.01

Table 2.2: Summary Statistics For Difference-in-Difference Sample

	Sample Means within 2.5 km		T-Stat of
	Before	After	Difference
Characteristics of Birth			
Birthweight	3343.234	3310.302	2.70**
Term Birth Weight	3418.39	3383.15	3.30***
Gestation Length	38.676	38.658	0.43
Premature	0.077	0.078	-0.12
Low birth weight (LBW)	0.055	0.063	-1.52
Small for gestational age (SGA)	0.098	0.106	-1.25
APGAR 5 minute	8.884	8.88	0.33
Mother's Demographic Characteristics			
Dropout	0.112	0.119	-1.0
High School	0.297	0.287	0.97
Some college	0.299	0.293	0.69
College plus	0.289	0.299	-1.08
Teen Mom	0.048	0.049	-0.3
Mom Aged 19-24	0.267	0.274	-0.66
Mom Aged 25-34	0.545	0.56	-1.35
Mom Aged 35 and older	0.14	0.117	3.08**
Black	0.025	0.024	0.07
Hispanic	0.011	0.01	0.58
Smoked during pregnancy	0.299	0.3	-0.12
Married	0.633	0.626	0.67
WIC	0.395	0.426	-2.92**
Medicaid	0.32	0.375	-5.43***
Private Insurance	0.569	0.55	1.81
Sample Size	19246	2364	

Source: Author calculations from Pennsylvania Department of Health Vital Statistics.
* p<0.10, ** p<0.05, *** p<0.01

Table 2.3: Pre- and Post- Drilling Differences in Average Characteristics of Births Close to Well Locations

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
			Characteristic of Mother					
	LBW	Term Birth Weight	Education (years)	Teen Mom	Dropout	Black	Smoked	Born in PA
			Panel A: Pre-drilling differences in characteristiscs					
Within 2.5 km of well	-0.00196	9.520*	-0.290***	0.00261	0.0067	-0.00735	0.00959	0.0301***
	(0.0019)	(4.794)	(0.0903)	(0.00337)	(0.00998)	(0.00607)	(0.0104)	(0.00862)
Sample Size	43522	40175	43426	43582	43582	43582	43582	43582
R^2	0.004	0.01	0.063	0.009	0.028	0.016	0.024	0.018
		Panel B: Differences in characteristiscs for analysis sample using DD estimator						
Within 2.5 km * post-drilling			0.310***	0.000550	-0.0132	0.00343	0.00277	-0.0222
			(0.0944)	(0.00666)	(0.0118)	(0.00308)	(0.0196)	(0.0163)
Sample Size			21581	21646	21646	21646	21646	21646
R^2			0.066	0.012	0.039	0.016	0.026	0.020

Notes: Each coefficient is from a different regression. Pre-drilling (post-drilling) refers to births that occur before (after) the spud date of the closest well. Standard errors are clustered at the mother's residence county. All regressions include indicators for month and year of birth, their interactions and residence county indicators. Source: Author calculations from Pennsylvania Department of Health Vital Statistics. Significance: * p<0.10, ** p<0.05, *** p<0.01.

Table 2.4: Impact of Well Location on Low and Term Birth Weight

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	Pre-drilling (5 km)				*Pre- and post- drilling (2.5 km)*			
	Low Birth Weight		Term Birth Weight		Low Birth Weight		Term Birth Weight	
Within 2.5 km of well	-0.00196	-0.00240	9.52*	15.16***	-0.000790	-0.00178	18.2	24.01
	(0.0019)	(0.00198)	(4.794)	(4.784)	(0.00272)	(0.00320)	(18.53)	(15.56)
Post-drilling					-0.0101	-0.00824	6.088	23.79**
					(0.00879)	(0.00873)	(10.75)	(9.352)
Within 2.5 km * post-drilling					0.0144**	0.0136**	-47.82***	-49.58***
					(0.00537)	(0.00511)	(15.12)	(14.04)
Sample Size	43522	43522	40175	40175	21610	21610	19978	19978
R^2	0.004	0.018	0.0099	0.074	0.008	0.021	0.013	0.075
Maternal Characteristics	no	yes	no	yes	no	yes	no	yes

Notes: Each coefficient is from a different regression. Pre-drilling(post-drilling) refers to births that occur before (after) the spud date of well within 2.5 km. Standard errors are clustered at the mother's residence county. The sample is limited to singleton births. All regressions include indicators for month and year of birth, their interactions, residence county indicators, an indicator for drilling before birth (defined by closest well), an indicator for specified distance from a well or future well/permit and the interaction of interest reported above. Maternal characteristics include mother black, mother Hispanic, mother education (hs, some college, college), mother age (19-24,25-34, 35+), female child, WIC, smoking during pregnancy, marital status and payment type (private insurance, medicaid, self-pay, other). Standard errors are in parentheses and clustered at the mother's residence county. For pre-drilling, columns (1)-(4) contain all observations within 5 km of a well or permit prior to drilling. For pre- and post-drilling, columns (5)-(8) contain the primary research sample: those residences within 2.5 km of a well or permit, before and after drilling. Signifance: * p<0.10, ** p<0.05, *** p<0.01.

Table 2.5: Difference-in-Difference Estimates of the Effect of Drilling on Health at Birth by Proximity

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	Birth Weight		APGAR < 8		Gestation (weeks)		Premature	
Within 2.5 km * post-drilling	-46.16***	-46.62***	0.0254**	0.0251**	-0.0811	-0.0771	0.000517	-0.000343
	(13.84)	(12.52)	(0.0099)	(0.0101)	(0.0559)	(0.0513)	(0.00616)	(0.00681)
Sample Size	21610	21610	21646	21646	21204	21204	21204	21204
R^2	0.013	0.061	0.026	0.029	0.014	0.021	0.008	0.012
	SGA		Congenital Anomaly		Infant Death		Summary Index	
Within 2.5 km * post-drilling	0.0180**	0.0181**	-0.00210	-0.00193	-0.00079	-0.00075	0.0255**	0.0264**
	(0.00720)	(0.00764)	(0.00194)	(0.00189)	(0.00149)	(0.00143)	(0.0105)	(0.0101)
Sample Size	21524	21524	21646	21646	21646	21646	21646	21646
R^2	0.008	0.040	0.006	0.008	0.007	0.042	0.014	0.045
Maternal Characteristics	no	yes	no	yes	no	yes	no	yes

Each coefficient is from a different regression. Pre-drilling(post-drilling) refers to births that occur before (after) the spud date of well within 2.5 km. Standard errors are clustered at the mother's residence county. The sample is limited to singleton births. All regressions include indicators for month and year of birth, their interactions, residence county indicators, an indicator for drilling before birth (defined by closest well), an indicator for specified distance from a well or future well/permit and the interaction of interest reported above. Maternal characteristics include mother black, mother Hispanic, mother education (hs, some college, college), mother age (19-24,25-34, 35+), female child, WIC, smoking during pregnancy, marital status and payment type (private insurance, medicaid, self-pay, other). Standard errors are in parentheses and clustered at the mother's residence county. Source: Author calculations from Pennsylvania Department of Health Vital Statistics. Significance: * p<0.10, ** p<0.05, *** p<0.01.

Table 2.6: The Effect of Shale Gas Extraction on Birth Outcomes, Mother Fixed Effects

	(1)	(2)	(3)	(4)	(5)
	LBW	TBW	Summary Index	Premature	SGA
Within 2.5 km * post	0.0151	-19.07	0.0168	-0.00800	0.00707
	(0.0135)	(24.44)	(0.0573)	(0.0162)	(0.0171)
Sample Size	15,982	14,790	16,009	15,683	15,937
R^2	0.554	0.699	0.559	0.556	0.563

Notes: See Table 2.4. Each column is a different regression. The sample is defined by mothers who have multiple singleton births during 2003-2010 and were living during at least one birth within 2.5 km of a well or future well. Each regression includes time and county fixed effects, time-varying mother characteristics and mother fixed effects. Standard errors are clustered at the mother. Source: Author calculations from Pennsylvania Department of Health Vital Statistics. Note: LBW= low birth weight; TWB= term birth weight; SGA= small for gestational age. Significance: * p<0.10, ** p<0.05, *** p<0.01.

Table 2.7: The Effect of Shale Gas Extraction on Birth Outcomes by Water Source

	(1)	(2)	(3)	(4)	(5)
	LBW	TBW	Summary Index	Premature	SGA
Post	-0.00357	60.42**	-0.0255	0.0290***	-0.0217
	(0.00909)	(29.20)	(0.0350)	(0.00874)	(0.0199)
Within 2.5 km * post	0.00782	-80.11**	0.110**	-0.0202**	0.0308*
	(0.0118)	(30.79)	(0.0450)	(0.00946)	(0.0179)
PWSA * post	-0.00573	-44.74*	0.0131	-0.0278***	0.00245
	(0.00546)	(26.48)	(0.0561)	(0.00577)	(0.0153)
PWSA * within 2.5 km * post	0.00704	32.32	-0.0541	0.0249	-0.0160
	(0.0161)	(33.29)	(0.0657)	(0.0154)	(0.0196)
Sample Size	21,610	19,978	21646	21,204	21,524
R^2	0.021	0.075	0.047	0.013	0.040

Notes: See Table 2.4. Each column is a different regression. The full model is a triple difference, with important coefficients reported above. Source: Author calculations from Pennsylvania Department of Health Vital Statistics. Note: LBW= low birth weight; TWB= term birth weight; SGA= small for gestational age. PWSA is an indicator equal to one if the maternal residence receives piped public water from a public water service area (PWSA) and equal to zero if the maternal residence uses private well water. Significance: * p<0.10, ** p<0.05, *** p<0.01.

Table 2.8: The Effect of Shale Gas Extraction on Birth Outcomes by Maternal Mobility

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
		Non-Movers			Movers		
	Moved	LBW	TBW	Summary Index	LBW	TBW	Summary Index
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Within 2.5 km * post	0.022	0.0117	-59.11**	.0812**	0.00951	-59.24	0.148***
	(0.0139)	(0.0123)	(22.59)	(0.0321)	(0.0165)	(38.36)	(0.0557)
Sample Size	16008	11860	10975	11879	4121	3814	4129
R^2	0.196	0.035	0.094	0.063	0.06	0.13	0.087

Notes: See Table 2.4. Each column is a different regression. Source: Author calculations from Pennsylvania Department of Health Vital Statistics. Note: LBW= low birth weight; TWB= term birth weight. Significance: * p<0.10, ** p<0.05, *** p<0.01.

Table 2.9: Robustness Checks, Shale Gas Development on Birth Measures

	(1)	(2)	(3)	(4)
	Low Birth Weight	Term Birth Weight	Birth Weight	Small for Gestational Age
Panel A: +/- 2 years				
Within 2.5 km * post	0.0133	-39.0261	-38.8751	0.0198
	(0.008)*	(20.857)*	(19.827)*	(0.009)**
R^2	0.013	0.069	0.052	0.038
Observations	12930	11964	12930	12919
Panel B: All observations 2008-2010				
Within 2.5 km * post	0.0189	-31.4895	-54.8326	0.0251
	(0.011)*	(24.001)	(24.471)**	(0.013)*
R^2	0.016	0.068	0.054	0.047
Observations	7189	6674	7189	7180
Panel C: Number of wells and continuous distance				
Within 2.5 km * post	0.0132	-49.8154	-46.3336	0.0176
	(0.005)**	(14.379)***	(13.184)***	(0.008)**
R^2	0.021	0.076	0.061	0.040
Observations	21524	19898	21524	21439
Panel D: African American only				
Within 2.5 km * post	-0.0224	-81.6538	-18.0341	-0.0432
	(0.099)	(82.052)	(99.389)	(0.046)
R^2	0.107	0.144	0.112	0.158
Observations	531	482	531	531
Panel E: Smokers only				
Within 2.5 km * post	0.0194	-62.2487	-46.5296	0.0080
	(0.014)	(34.525)*	(39.532)	(0.026)
R^2	0.023	0.051	0.047	0.028
Observations	6465	5903	6465	6436
Panel F: High school dropouts only				
Within 2.5 km * post	0.0478	-79.9855	-104.6243	0.0169
	(0.028)*	(46.064)*	(58.259)*	(0.033)
R^2	0.040	0.105	0.089	0.058
Observations	2434	2221	2434	2428

Notes: See Table 2.4. Each panel is a separate regression. All regressions include controls for maternal characteristics and county-time trends. Source: Author calculations from Pennsylvania Department of Health Vital Statistics. Significance: + p<0.15, * p<0.10, ** p<0.05, *** p<0.01.

Table 2.10: Falsification Tests on Impact of Well Location

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
	Baseline Estimates			Permit Date			Random date		
	LBW (1)	TBW (2)	Premature (3)	LBW (4)	TBW (5)	Premature (6)	LBW (7)	TBW (8)	Premature (9)
Within 2.5 km * post	0.0136**	-49.58***	-0.000343	-0.000106	-5.03	-0.00149	0.00103	-1.152	-0.00654
	(0.00511)	(14.04)	(0.00681)	(0.00682)	(12.382)	(0.00897)	(0.00303)	(11.5)	(.00789)
Sample Size	21610	19978	21204	19246	17795	18854	21610	19978	21204
R^2	0.021	0.075	0.012	0.009	0.013	0.009	0.021	0.075	0.012

Notes: See Table 2.4. Each panel is a separate regression. All regressions include controls for maternal characteristics and county-time trends. Columns (1), (2) and (3) are the baseline estimates from Tables 2.4 and 2.5. Columns (4) - (6) use permit date to define “treatment” and the coefficient reported is the interaction between an indicator for whether the permit was within 2.5 km from the mother’s residence and whether the birth occured after (post) the permit date. Columns (7)-(9) use a random date to define post birth. Source: Author calculations from Pennsylvania Department of Health Vital Statistics. LBW= low birth weight; TWB= term birth weight. Significance: * p<0.10, ** p<0.05, *** p<0.01.

CHAPTER 3

THE IMPACT OF OIL AND GAS EXTRACTION ON INFANT HEALTH IN COLORADO

The expansion of shale gas development in the US has brought with it a national debate that seemingly lacks a consensus over its economic, environmental, health and social implications. Shale gas has been promoted as a low-cost source of electricity, residential and commercial energy, industrial feed stocks, and even as transportation fuel. Natural gas provides an attractive source of energy because it emits fewer pollutants (e.g., carbon dioxide, sulfur dioxide, nitrogen oxides, carbon monoxide and particulate matter) when burned than other fossil-fuel energy sources per unit of heat produced.[1] However, public fears exist regarding the environmental effects (and subsequent public health effects) of shale gas development. Studies of US counties have shown that extraction of natural resources can have a positive effect on job creation and income in the short run (Weber, 2011; Marchand, 2012). Other studies have shown that the perceived risks and externalities of the process can have detrimental effects on housing prices (Muehlenbachs et al., 2012). A few recent studies have made efforts to look at the health effects of unconventional methods using case studies, health impact assessments and toxicology to show that there are likely to be short and long term health effects (Bamberger and Oswald, 2012; McKenzie et al., 2012; Colborn et al., 2011).

Much of this debate centers around the recent growth in unconventional sources, such as shale gas, but mostly ignores more conventional forms of oil and gas development. In practice, conventional oil and gas, applies to oil and gas which can be extracted, after the drilling operations, just by the natural pressure of the wells and pumping or compression stations. However, throughout the last decade, conventional and unconventional

[1]Concerns about production and fugitive releases puts in question whether the life-cycle estimates are actually more favorable than coal.

resource extraction have benefited from new technologies that make these wells productive. The well stimulation process that has received the most attention in the media is called hydraulic fracturing (popularly known as "fracking"). Hydraulic fracturing stimulates the well using a combination of large quantities of water ("high-volume"), fracturing chemicals ("slick water") and sand, that are injected under ground at high pressure. This process fractures the rock and causes the resource to be released. Hydraulic fracturing has become prevalent in the last decade and according to the Colorado Oil and Gas Conservation Commission (COGCC), all of the $50,030$ oil and gas wells in Colorado were hydraulically fractured (as of June 2013).

In this paper, I combine data on oil, gas and coal bed methane extraction from the Colorado Oil and Gas Conservation Commission (COGCC) with data from birth certificate records from Colorado Department of Public Health and Environment (CDPHE) to estimate the infant health impacts of living in close proximity to a well during pregnancy. To date, there is no literature on infant health effects across resource extraction types (oil, shale gas, conventional natural gas and coal bed methane) or historical drilling. Colorado provides a unique environment to explore multiple extraction activities.

The difference-in-differences research design, which relies heavily on the assumption that the characteristics of mothers who live close to a completed well change over time in a similar manner to those who live a little further away, is tested by examining the observable characteristics of the mothers in these two groups. A range of specifications are estimated in an effort to provide evidence that the research design is robust. The results suggest both statistically and economically significant effects on infant health. The difference-in-difference models indicate that birth weight decreased and gestational lengths were reduced, on average. The estimates also indicate an increased prevalence of low birth weight and premature birth. The size of the effects are large and statistically significant at the 5 percent level. Perhaps surprisingly, the effect sizes for birth weight and low birth weight found in this study are very similar to the effect sizes found in Pennsylvania for only shale gas development, suggesting that any resource extraction near a pregnant woman's home will result in adverse birth outcomes (See Chapter 2).[2]

3.1 Oil and Gas Development in Colorado

3.1.1 Drilling and Production Overview

Figures 3.1, 3.2 and 3.3 provide an overview of the trends in drilling activity and production over the last 20 years. As with most states, natural gas drilling began to peak in the late 2000s with high prices and new technology. Some have called this the "shale gas revolution." In the case of Colorado, much of this new production is conventional natural gas. This provides context to the decade that this paper studies, 2000 – 2011.

3.1.2 Oil and Gas Development As A Potential Pollution Source

Preliminary evidence indicates that oil and gas development may produce waste that could contaminate the air, aquifers, waterways, and ecosystems that surround drilling sites or areas where water treatment facilities treat the waste water from the drilling process. However, there is little consensus about the likelihood of contamination, mechanisms or how widespread it might be (See Chapter 2 for a detailed discussion of the mechanisms).

For water pollution, faulty well casings, abandoned wells nearby or surface spills and accidents are considered the least controversial pathways (Osborn et al., 2011; Jackson

[2]The distance used to estimate the impact of shale gas development on infant health in Pennsylvania was 2.5 km. Reasons for different distances are discussed in the introduction of the dissertation.

et al., 2013; EPA, 2004; DEP, 2009; Lyverse and Unthank, 1988).[3] More controversial sources of ground water contamination are pathways between the shale formation and the aquifer, or if the drilling process occurs too close to a drinking water aquifer (Warner et al., 2012; DiGiulio et al., 2011). Migration of brine is theoretically possible, given certain assumptions, but the likelihood remains debated in the literature (Myers, 2012; Saiers and Barth, 2012). To date, there are only a few studies addressing ground and surface water contamination concerns and they take place mostly in Wyoming, Pennsylvania and Texas (DiGiulio et al., 2011; Osborn et al., 2011; Jackson et al., 2013; Olmstead et al., 2013).

Despite less attention in the media, air pollution is gaining more recent attention by researchers; sources of air pollution are expected with combustion activities, methane flaring and truck traffic (Witter et al., 2013; EPA, 2011). All stages of shale gas development have the potential to produce hazardous air pollution emissions (EPA, 2000, 2010, 2011). Air pollution has become a more immediate concern following some recent studies in Colorado that discovered higher levels of volatile organic compounds (VOCs), methane and other hydrocarbons near drilling sites (McKenzie et al., 2012; Colborn et al., 2012; Gilman et al., 2013; Pétron et al., 2012). Other emissions associated with combustion include particulate matter, polycyclic aromatic hydrocarbons, sulfur oxides and nitrogen oxides (Colborn et al., 2012; EPA, 2008). For example, CODPHE (2009) indicates that ambient benzene and VOC levels increased by 38% and 40%, respectively, from 1996 and 2007. These increases are likely related to the large increase in shale gas development in Garfield County, Colorado. Another example studied a well pad using a closed loop drilling system in Colorado and measured non-methane hydrocarbons throughout the drilling and production phases (Colborn et al., 2012). The authors also detected polycyclic aromatic hydrocarbons (PAHs) at greater concentrations within 1.1 km of the well pad than those at which prenatally exposed children in urban studies had lower devel-

[3] With virtually no pre-drilling samples of water wells near drilling sites, most studies are not considered conclusive.

opmental and IQ scores (Colborn et al., 2012).

In addition to the potential air pollution from the drilling process itself, traffic is often cited as a potential cause of increased ambient air pollution. Traffic is necessary to haul in and out drilling fluids, sand and drilling equipment. Volatile organic compounds (VOCs), which include BTEX and other hydrocarbons, and fugitive methane gas mix with nitrogen oxides (NO_x) from truck exhaust and produce ground-level ozone (Gilman et al., 2013).

3.1.3 Environmental Health Literature and Potential Mechanisms

The least controversial mechanism is air pollution and a few recent studies have identified the need for additional research focused on air pollution emissions for drilling operations (Colborn et al., 2012; McKenzie et al., 2012; Witter et al., 2013). The research design that follows is best suited to measure impacts on infant health from air pollution and has been widely used in the environmental health literature (Currie et al., 2011, 2009; Currie and Walker, 2011). See Chapter 2 for a detailed review of this recent literature. Remaining public health concerns identified are primarily related to increased stress for residents living near drilling sites. Although maternal stress and birth outcomes is an under-developed area of research, there are some recent studies that suggest a relationship between maternal stress and low birth weight and gestational age (Rondo et al., 2003; Dole et al., 2003; Camacho, 2008; Eskenazi et al., 2007; Lindo, 2011). Mothers living closest to drilling activity are most likely to be affected by noise, light and visible aspects of the drilling process.

Relying on this extensive literature exploring the relationship between infant health, air pollution and maternal health to provide biological plausibility to the results that follow, I build on the previous literature by using the natural experiment of the introduction of oil and gas wells, rich controls for confounding maternal characteristics, and homogenous groups of mothers to investigate the effects of shale gas development on infant health.

3.2 Data Sources

My analysis is based upon a data set acquired from the Colorado Oil and Gas Conservation Commission (COGCC) that contains information on each well drilled in Colorado since 1985. The data set contains information on location of well (latitude and longitude), spud date (timing that drilling began), first production date, test dates, total depth date (when vertical drilling completed), directional drilling (also called horizontal), resource type (i.e oil, gas or coal bed methane), geological formation, company, and other details.

My second source of data comes from birth certificate records from the Colorado Department of Public Health and the Environment (CDPHE). The natality records contain detailed information on every birth in the state including health at birth and background information on the mother and father which includes race, education, marital status, as well as, prenatal care and whether the mother smoked or drank alcohol during her pregnancy. My study makes use of the mother's exact address (geo-coded to latitude and longitude), which is merged to the oil and gas locations to define proximity to drilling.[4]

I make use of four primary health at birth outcomes.[5] Birth weight is defined as the weight of the infant measured at birth in grams. Gestation length is defined as the number of weeks of gestation. Low birth weight (LBW), defined as birth weight less than 2500

[4]CDPHE performed this merge and released the data stripped of geographical indicators, except those I requested specifying distance to nearest wells within 30 km of each mother's residence.

[5]Other outcomes that may be of interest, such as fetal/infant mortality and congenital anomalies are very rare events. When restricting the data set to those very close to gas wells or permits, there are insufficient cases in Pennsylvania for there to be a measurable effect for these outcomes.

grams, is commonly used as a key indicator of infant health, and hence is one of the outcomes examined. Premature birth, defined as gestation length less than 37 weeks, is associated with a greater risk for short and long term complications, including disabilities and impediments in growth and mental development. I also explore different levels of low birth weight and prematurity, as well as large for gestational age.

Table 3.1 provides summary statistics for the universe of births in Colorado from 2000-2011. The first column provides information on all births and the second column provides information on births to mothers' residences within 5 km of where an oil or gas well has been drilled or will eventually be drilled. The localized data I use in this analysis is actually quite similar to the characteristics of the rest of the state. Column 3 provides a decomposition of birth weight of residences within 2 km of a well to gauge the importance of the various observable mother characteristics. These control variables are included in all my subsequent regression analysis, but, for simplicity, I do no report these coefficients in the tables below.

Table 3.2 provides summary statistics for the primary difference-in-difference (DD) analysis sample. In the analysis that follows, the sample is restricted to those mothers' residences within 5 km of an oil or gas well that was drilled within 2 years (before and after) of the timing of birth.[6]. In the DD model, I compare residences within 1 km of a gas well to those $1-5$ km from a gas well, before and after drilling. The cross-sectional differences in sample means for characteristics of birth, mother's demographic characteristics and characteristics of oil and gas development nearby are reported in Table 3.2. Most of the statistically significant differences between these two samples are actually not very economically important; this is likely a result of the large analysis sample. However, mother characteristics closest to wells (1 km) are indicative of better socio-economic status, versus those further away ($1-5$ km). Those mothers who reside within 1 km are

[6]The entire sample of births within 2 km of any oil and gas well, regardless of spud date is $74,903$; $39,221$ of which have mother residences within 1 km of a well.

more educated, more white, less likely to smoke while pregnant, and more likely to be married. I control for the observable characteristics of the mother in the empirical specifications that follow.

Table 3.2 also contains some information about the levels of exposure of oil and gas development in these communities. The intensity of drilling for those very close to development is much greater than those a little further away: those living 1 km from a well are near 126 wells on average compared to 45 wells for those further away. The average number of wells within 5 km of the maternal address drilled in the year of birth is fairly similar, however.

3.3 Empirical Methodology

Since air or water pollution are not randomly assigned, studies that attempt to compare health outcomes for populations exposed to differing pollution levels may not adequately control for confounding determinants of health. In the absence of a randomized trial, this paper exploits the variation over time in the introduction of oil and gas development in Colorado during 2000 – 2011. Rather than compare aggregated areas, I know the specific location where oil and gas drilling has taken place and the dates of when drilling began. The specific location data allow me to compare health at birth within very small areas in which mothers are likely to be more homogeneous in observable and unobservable characteristics than in normal aggregate comparisons. The next two sections provide graphical evidence and explain the estimation strategy in detail.

3.3.1 Graphical Evidence

If living close to a drilled well has a negative impact on infant health at birth, we should see average birth weight for mother's residences in close proximity to wells fall subsequent to when drilling begins. Moreover, we should observe larger impacts for homes closest to drilling activity. Figure 3.4 shows the birth weight gradient of distance to closest well before and after drilling. There is a clear decline in birth weight with proximity to a well that persists up to 5 km away. Figure 3.5 shows similar results for gestation length in weeks.

The notion that the reduction in birth weight (gestation) close to a well reflects the causal impact of beginning drilling activity would be supported if the decline coincides with when drilling begins and does not reflect a preexisting downward trend in birth weight (gestation) for these mother's residences. Figures 3.6 and 3.7 show the birth weight and gestation gradients of time with respect to when drilling begins within 1 km and between 1 and 5 km of the well locations. This gradient is measured for births 500 days before and after drilling. If the birth weight decline showed in figures 3.4 and 3.5 reflected a preexisting trend, we would see a consistent downward trend over this time period. Instead, I find a fairly sharp decrease in birth weights coincident with the spud dates (defined as time=0).[7] For gestation periods, there does appear to be a downward trend for both the treatment and the control group after drilling, but this is taken into account in the DD design.

[7]The spud date is the date that the drill bit hit the ground, but building the well pad happens about $1-3$ months prior to that date on average. These graphs also use birth date as the relevant date, when it is unlikely that drilling happening on the child's birth date would influence birth outcomes. Due to the somewhat fuzzy nature of this timing, there does appear to be a slight trend prior to time=0. However, without well-specific information about timing of well pad construction, as well as information about timing of drilling during pregnancy that may matter for birth outcomes, I provide a raw graph here.

To define the distance of interest, I also look at the residuals of the birth weight regression over distance. These are shown in figure 3.8. There is a clear divergence in residuals closest to a well that seem to persist out to about 1.5 km. This supports the use of 1 km as the primary effected group. In appendix Table B.2, I present the main results for distances 0.5 km up to 2 km and the results are qualitatively similar when I use 1 km as when I use 1.5 km.

3.3.2 Statistical Estimation Framework

Inspired by the graphical evidence, I proceed with estimating empirical models that include a cross-sectional difference estimator and a difference-in-difference estimator. First, I use the cross-sectional difference estimator to check for pre-existing differences in the characteristics of mothers whose residences are located within 1 km and between $1-5$ km of an oil or gas well. Given similarity, I then use a difference-in-differences model —in which mothers exposed in residences $1-5$ km from a well are used as controls for mothers exposed within 1 km— to estimate the impact of exposure to oil and gas extraction on health at birth measures.

The cross-sectional difference specification takes the following form:

$$Outcome_{it} = Year_t + \beta_1 D_{it}^{1km} + \epsilon_{it} \tag{3.1}$$

Health at birth (4 measures) is a function of a measure of distance from the resource well, a random error term (allowing for year specific correlation in health by county), and $Year_{it}$, a year specific effect. D_{it}^{1km} is an indicator variable set to one if the mother's residence is within 1 km of a well. To examine variation in other mother characteristics, I substitute those characteristics for $Outcome_{it}$ as the dependent variable.

The difference-in-difference specification adds an indicator variable for whether the birth took place after a well was drilled ($Post_{it}$), an indicator of whether the residence was 1 km from a current or future well head (D_{it}^{1km}) and the interactions ($D_{it}^{1km} * Post_{it}$). Thus, the counterfactual change in infant health for mother's residences close to an oil or gas well is estimated using residences just slightly further away. It also includes zip code and quarter of birth-year fixed effects ($Qtr_{it} * Year_{it} + Zip_{it}$) and observable mother and birth characteristics (X_{it}):

$$\begin{aligned} Outcome_{it} = \omega_1 D_{it}^{1km} * Post_{it} + \epsilon_{it} + \delta_0 D_{it}^{1km} + \delta_1 Post_{it} \\ + Qtr_{it} + Year_{it} + Qtr_{it} * Year_{it} + Zip_{it} + \beta_0 X_{it} \\ + \end{aligned} \tag{3.2}$$

The estimated impact of oil and gas drilling on infant health is given by the term ω_1 and is the difference-in-differences estimator. Zip_{it} is designed to capture any unobserved time-invariant characteristics of each zip code in the sample. $Year_{it}$ and Qtr_{it} are included to allow for systematic trends over time within each zip code. Quarter and year are interacted to control for secular time-trends. The standard errors in these models are clustered at the mother's residence zip code. The vector X_{it} contains mother and child characteristics including indicators for whether the mother is White, Black, Asian, other race (left out category) and/or Hispanic, four mother education categories (less than high school (left out category), high school, some college, and college or more), mother age categories (teen (left out category), 19-24, 25-34 and 35+), indicators for smoking or drinking during pregnancy, mother's marital status, previous risky pregnancy, current risky pregnancy, parity and an indicator for sex of the child.

Relying on cross-sectional variation alone, however, would be problematic if mother characteristics vary within a small radius of interest that are unobservable to the researcher. If, for example, the location of oil and gas drilling occurs where the neighborhoods are already economically distressed, then the variation in health outcomes may reflect socio-economic status, as opposed to living in close proximity to resource extraction.

This is a constant concern in the literature that attempts to exploit variation in health at birth (see Currie (2011)). I therefore examine within-neighborhood in health at birth outcomes shortly before and after oil and gas drilling. Reducing the sample to a 4 year window (2 years before and after) limits the amount of migration that can occur that may be due to oil and gas development. It also ensures that the wells of interest have recently been drilled, so that the identification strategy is not dependent on wells that are older than 2 years. This will also make potential exposures more homogeneous, as the scientific literature is still determining at which part of the life course of a well is pollution emissions most likely (e.g. when first drilled, at first production or when the well is old).[8]

One important caveat in my empirical strategy is that, like all such studies, I can observe health at birth for only those babies that are born alive. Also, I can only observe births for those mothers who choose to get pregnant. If the composition of mothers choosing to get pregnant changes with the introduction of resource extraction, then the health that I observe may not be indicative of the average health of those living near wells in these neighborhoods. It is possible that mothers who value their children's health are more likely to move away from communities where drilling is taking place. This migratory effect would lower the average health of the observed births. However, it is also possible that those who are more likely to move are families who are experiencing the worse health effects of drilling. This migratory effect would increase the average health of the

[8]Current estimates are showing air pollution emissions throughout the life of the well (Colborn et al., 2012).

observed births. Thus, it is not clear whether selection or composition of the mother characteristics would lead me to overestimate or underestimate the health impacts of close proximity to drilling activity. This issue is present in all empirical work using vital statistics, where each birth occurs only once. Unfortunately, without data on all women who are child-bearing age and their characteristics, residential decisions and fertility decisions, I cannot examine this issue in this context.

3.4 Estimation Results

3.4.1 Differences in Characteristics of Mother's Close to a Well

My estimation strategy hinges on the relative similarity between mothers residing within 1 km of a well to mothers residing 1 – 5 km of a well at the time of the observed birth. While this is somewhat supported by the graphical evidence, I formally estimate these differences. I proceed by estimating equation (3.1) using residences within 5 km of a well.

First, I limit the sample to births that took place before the drilling began (Table 3.3, Panel A). I find little evidence of any preexisting differences in either health at birth or mother characteristics that would be indicative of worse health trends in these communities prior to drilling. Although the differences are statistically significant, these communities boast heavier babies, more education, and less teen moms prior to drilling within 1 km of a future well. All of these characteristics indicate potentially better health outcomes, not worse. This does suggest selection into the locations where drilling takes place, but it goes in a direction that we may not have anticipated. Often, new industrial activity is correlated with poor, less educated communities. Fortunately, any bias would push these estimates towards a null effect and any adverse effects detected are certainly not reflective of a pre-existing adverse health trend.

To further test the validity of my research design, I also estimate equation 4.4.3 and use the difference-in-difference estimator to determine if there are any changes in mother characteristics after drilling began. Results are reported in Table 3.3, Panel B. Mothers who gave birth after drilling occurred within 1 km of their residence have an increased likelihood to be teen moms. Although this shows a change in the composition of mothers, teen moms still make up a very small proportion of the population. I include controls for these and more characteristics in all specifications to help account for these observed changes as well as unobserved changes.

3.4.2 The Impact of Oil and Gas Extraction

For illustrative purposes, I first present estimates of equation (3.1) in Table 3.4 Panel A, including zip code and quarter-year of birth fixed effects, but no other control variables. The second column for each measure includes maternal characteristics. The estimate from this specification is simply a measure of the average difference in the birth outcomes for those residences within 1 km of a future oil or gas well. Similar to what was found for maternal characteristics in Table 3.3 Panel A, these differences suggest that birth outcomes may have been better off prior to drilling. Prior to drilling, birth weights were 52 grams heavier on average, gestation periods were about 13% longer, and the prevalence of low birth weight and premature birth was reduced by 1.5 and 2.5 percentage points, respectively compared to mothers who lived $1-5$ km away from a future well. These results confirm that neonatal health close to drilling sites had a positive trend prior to drilling.

For each of the estimates that follow, I present them with and without maternal characteristics. Estimates with and without characteristics do not change much in magnitude or significance, providing confidence in the estimation strategy. Estimating equation (4.4.3) in Table 3.4 Panel B– my difference-in-difference specification– I find that birth outcomes are adversely affected by drilling activity within 1 km of the maternal residence. The estimate for birth weight is -35.79 grams, with mother characteristics included, and is statistically significant at the 1 percent level. To explore if this effect is persistent, I also estimate equation (4.4.3) using 1.5 km and find a persistent, but less precise, reduction of birth weight of 25.55 grams, on average. This effect does not persist past 2 km and suggests that there may be a threshold of exposure between 1.5 – 2 km from a well head (approximately 1 mile).[9] In addition to reduced average birth weight, residences within 1 km of a well have births with reduced gestational periods, increased prevalence of LBW of 1.70 percentage points and increased prevalence of premature birth of 2.15 percentage points. These estimates are all statistically significant at the 5 percent level and most are significant at the 1 percent level.

In the appendix, I include Table B.3 which presents difference-in-difference estimates for the four birth outcomes for the years 2007 – 2011. The birth certificate records changed in 2007 to include mother's income, insurance status, and whether she received public support from Women Infants and Children (WIC). To make sure that the results are robust to additional controls, especially controls for socio-economic status like income and insurance, I replicate the main table using this sub-sample. For each health measure, I provide 2 columns. The first column includes the same controls as the rest of the paper and the second column adds these additional income/insurance controls. The results suggest that a drilled well within 1 km of a mother's residence from 2007 – 2011 results in a decreased birth weight of 30.7 grams and a reduced gestational period of 0.10 weeks, on average. The estimates also suggest a 2.03 percentage point increase in low birth weight and a 1.16 percentage point increase in premature birth. Only the premature estimate becomes less precise with the inclusion of expanded controls for income. These estimates

[9]See Appendix Table B.2 for these results.

also suggest that the main results in the paper are not driven by earlier time periods and that the impacts of close proximity to resource extraction wells remain persistent in more recent years.

Levels of Low Birth Weight and Premature Birth

Low birth weight and premature birth are arguably arbitrary cut-offs and are an attempt to get at a latent variable- the threshold at which children require additional medical support in their first few weeks of life. Table 3.5 reports three categories of severity for each of these measures. Exposure to oil and gas extraction increased the rate of all thresholds of these negative outcomes. For levels of low birth weight, oil and gas extraction primarily increased the probability of being slightly low birth weight by 1.1 percentage points and increase the probability of being very low birth weight by 0.3 percentage points. In contrast, exposure increased the rate of all levels of premature birth: the probability of being slightly premature ($34-37$ weeks) increased by 1.4 percentage points, the probability of being moderately premature ($32-34$ weeks) increased by 0.3 percentage points and the probability of being very premature increased by 0.5 percentage points.

Maternal Health and Health Care

A growing literature has looked at maternal health to identify stress during pregnancy (Camacho, 2008; Eccleston, 2011). This literature uses hypertension, eclampsia, diabetes and genital herpes as medical risk factors correlated with maternal stress. Hypertension, eclampsia and gestational diabetes have also been linked to air pollution exposure during pregnancy in the epidemiology literature. Additionally, labor complications have been associated with stress during pregnancy as well. Table 3.6 presents results using the difference-in-differences estimator to look at these factors. Interestingly, living within 1 km of an oil or gas well increases the probability of one of these risk factors by 1.1 percentage points. Labor complications may also increase, but is not precisely estimated. I do not find increased prevalence of lung disease, but maternal asthma is not well reported in these data. Large for gestational age is likely to increase with gestational diabetes, but this does not appear to happen in this sample. I do not find any changes in prenatal care of the moms associated with oil and gas extraction. The male/female sex ratio has been used to measure selection into live birth and here I find a reduction in the number of males after drilling by 1.6 percentage points.

Gender Specific Effects

One of the ways to test whether there is selection into observed live births is to look at the ratio of males to females in the sample.[10] Another is to look at whether there are differences across genders in the reported effects. Table 3.7 presents the results separately for males and females. The majority of the coefficients are statistically equivalent and suggest that the effects of exposure are similar across genders, on average.

3.4.3 Robustness Checks

To provide additional support for the research design, I perform a few robustness checks. Birth outcomes are associated with different subgroups, as shown in the marginal effects reported in Table 3.1. In Table 3.8, I present results for various potentially important subgroups. Most notably, the results for white non-Hispanic mothers are quite a bit more pronounced than the main results in the paper. And the results for smokers are very large, suggesting that maternal smoking may have a compounding effect.[11] Some may be

[10]These were reported in the last section.
[11]This has been found in other papers as well (Currie et al., 2009).

concerned that migration is driving these results. Although it is an imperfect measure, I find very similar results for mothers who were born in Colorado.

Due to the imprecise nature of the oil and gas well dates, I also estimate the main results using conception date as the date of interest. These results are reported in the Appendix Table B.5 and are qualitatively similar.

Most of the results reported in this paper use zip code fixed effects. I have also estimated all of the results using county fixed effects that also include $county * year * quarter$ fixed effects. A comparison with the main results are reported in Appendix Table B.1. Choice of location fixed effects does not appreciably change the results.

To ensure that the results are not driven by the choice of the comparison group, I also estimate the main results using a comparison group that is $1-2$ km from the well head (as opposed to $1-5$ km). These results are reported in Appendix Table B.4. Again, this change in specification does not affect the reported results.

3.4.4 Placebo Regression

Due to my analysis showing evidence of preexisting differences in the communities located closest to drilled wells relative to communities close to future wells or those who live a little further away, I employ a few placebo regressions. Even though the trends are suggestive of better outcomes prior to drilling, it is theoretically possible that the increase in adverse birth outcomes after drilling is driven by differential trends in fertility or migration post-drilling. I investigate this possibility by estimating equation (4.4.3) using false spud dates 2 years prior to the actual spud date to define exposure. Table 3.9 presents baseline estimates and the results of this placebo regression and I find no evidence of a spurious effect.

Using a date that is a fixed number of years prior may not be a suitable choice if different communities systematically are exposed at different times. To address this, I also perform checks using two random dates, one relative to the spud date and one relative to the birth date. Using a uniform distribution, I create a random date based upon the number of days in the year of spud or birth and then allow the year to change randomly 5 years before and after. These results in Table 3.9 also show no statistically significant effects and provide support for the research design employed.

3.5 Discussion and Interpretation

There are four main findings in this paper. First, my results suggest that oil and gas extraction can have adverse effects on the health of people living nearby, namely that of prenatal infants. Babies born of mothers who lived within 1 km of an oil or gas well during pregnancy had lower birth weights on average after drilling than prior to drilling. Oil and gas extraction increased the incidence of low birth weight and premature birth in the vicinity of a well by 31 percent and 33 percent, respectively. Furthermore, birth weight and gestation were decreased by 35.8 grams (1.1 percent) and 0.11 weeks (0.3 percent) on average, respectively. While these impacts are remarkably large, they are biologically plausible given the correlations between air pollution (or maternal stress) and birth outcomes found in previous studies. For example, Zahran et al. (2012) found exposure to benzene reduced birth weight by 16.5 grams and increased the odds of a very low birth weight event by a multiplicative factor, and Slama et al. (2009) found that exposure to benzene reduced birth weight by 77 grams on average. For context, Almond et al. (2005) found that smoking reduces a child's birth weight by about 202 grams. Given the wealth of studies that identify a causal link between birth weights and long-run outcomes, these impacts are likely to persist throughout these children's lives (Johnson and Schoeni, 2011;

Black et al., 2007).

Second, the results for maternal risk factors are suggestive of increased stress and exposure to ambient air pollution. These results begin to clarify the likely mechanisms that explain the infant health results.

Third, the results for different levels of low birth weight and premature birth suggest that oil and gas extraction are not merely increasing those that fall below the threshold, but that there is also an increase in very low birth weight and very premature birth. This suggests that the communities exposed may experienced increased infant mortality and certainly higher health care costs associated with these more vulnerable infants.

Fourth, these results suggest that both conventional and unconventional oil and gas development can have adverse impacts on birth outcomes, not just shale gas ("fracking").

Cost Estimates

A recent report from the Institute of Medicine estimates that the cost to society of low birth weight and premature infants is $51,600 per infant for the first year of health care costs (in 2005 dollars, Behrman and Butler (2007)). A different estimate in the same year found that each preterm/low birth weight baby incurs an average of $15,100 additional hospital costs in the first year of life (Russell et al., 2007). I use this lower bound for my cost calculations. Each low birth weight infant is fifty percent more likely to require special education services and each special education child costs the state of Pennsylvania $10,404 in 2007 (Chaikind and Corman, 1991; Augenblick et al., 2007). Following Currie et al. (2013a) and Chapter 2, I use their estimate of discounted life time wages due to low birth weight of $76,800.[12] Combining hospital costs attributable to low birth weight ($15,100 in additional hospital costs), estimates for special education services ($5,200) and

[12]See Currie et al. (2013a) for more details regarding this calculation.

decreased earnings ($76,800), an arguably conservative estimate is $96,500 in added cost of low birth weight children.[13] This translates to a cost of $8.5 million for those infants born within 1 km of an oil or gas well in Colorado from 2000-2011.

3.6 Conclusion

My study seeks to understand and quantify the impacts of oil and gas extraction on infant health. The chemicals used during drilling, cleaning drill rigs and hydraulic fracturing are linked to birth defects, cancer and reduced lung function, but there is little guidance from the scientific literature about the magnitude, time horizon or likelihood of these effects. Additionally, recent studies have shown an increase in air pollution associated with drilling, but little research has been done to assess how far these air pollutants can travel.

As a first step, I assembled a unique data set with the latitude and longitude of new mothers and the locations of oil and gas wells and permits in Colorado. I examine the impacts of living in close proximity to development on low birth weight, birth weight and premature birth using a difference-in-difference estimation strategy. Using very detailed data on the locations of oil and gas wells in Colorado and the dates they are drilled, I estimate that, on average, mothers living within 1 km of a well have reduced birth weight babies and reduced gestation. I also find increased prevalence of low birth weight and premature birth in these communities.

It is clear from these results that policies intended to mitigate the risks of oil and gas development can have significant health benefits. I find detectable effects of oil and gas development up to 1.5 km from the well head. Current required set back distances (dis-

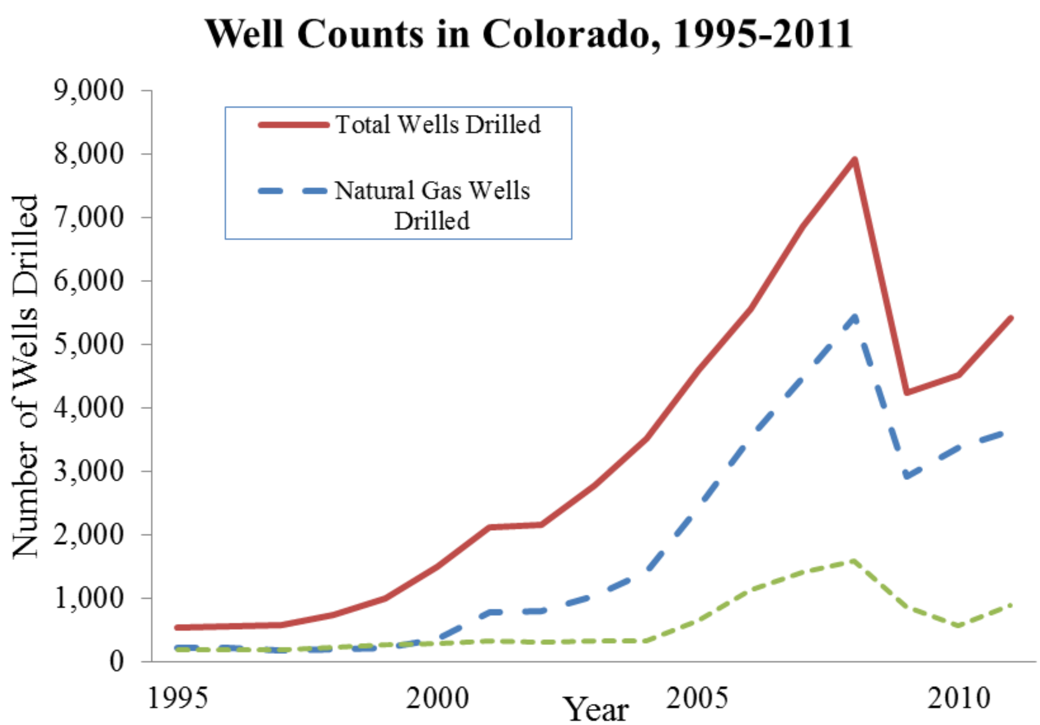
[13]This figure excludes medical bills after the first year and, hence, a lower bound estimate.

tance between well head and nearby residences, hospitals and schools) range from 300 ft to 800 ft across the 34 states where oil and gas development is taking place. With detectable infant health effects up to 1 mile away, these set back distances may be deemed insufficient to protect human health. This finding also adds impetus for regulators to increase regulations that reduce air pollution emissions from drilling operations and for industry actors to increase voluntary action to reduce air pollution emissions.

While the economic benefits of oil and gas development are easily quantifiable, there may be some hidden costs. Given that low birth weight and premature birth are strong predictors of education, labor force participation, reduced earnings and future health, the long term costs could be very high for these communities.

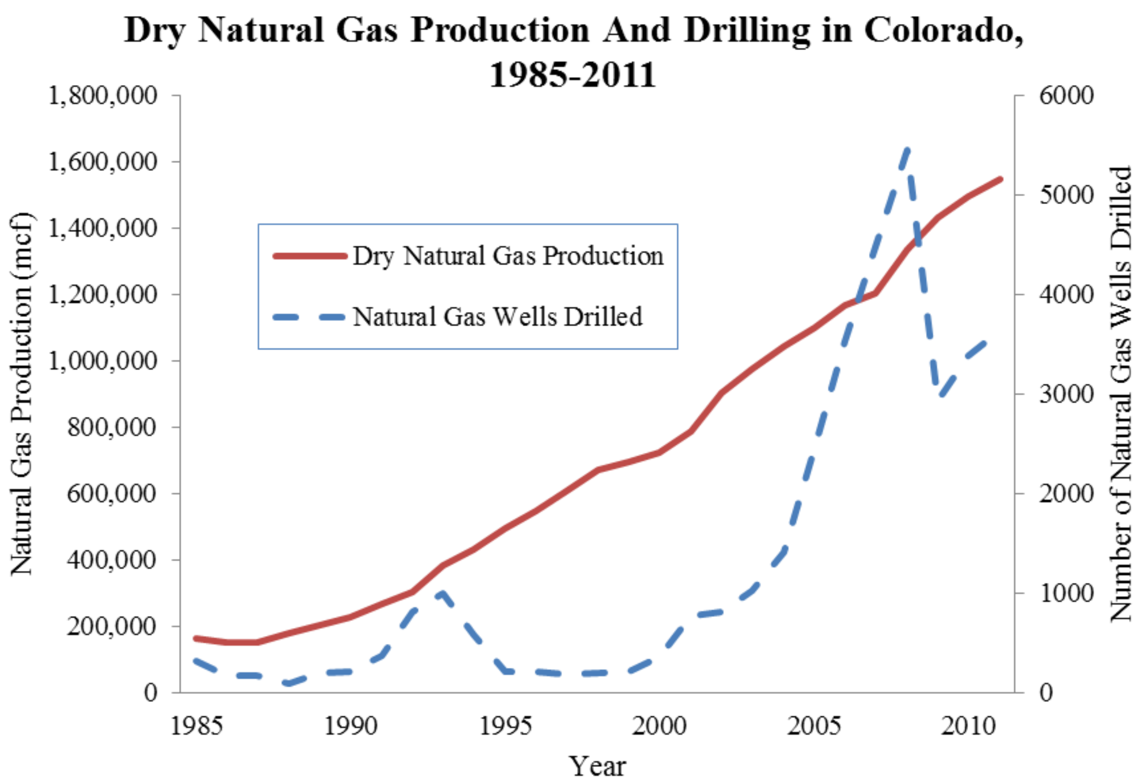
Further research to inform policy makers about the precise mechanisms of exposure is sorely needed. Additionally, if we think of infant health as the "canary in the coal mine", more research on the health impacts to children and adults, as well as longer term impacts, is certainly warranted.

Figure 3.1: Wells Drilled by Resource Type



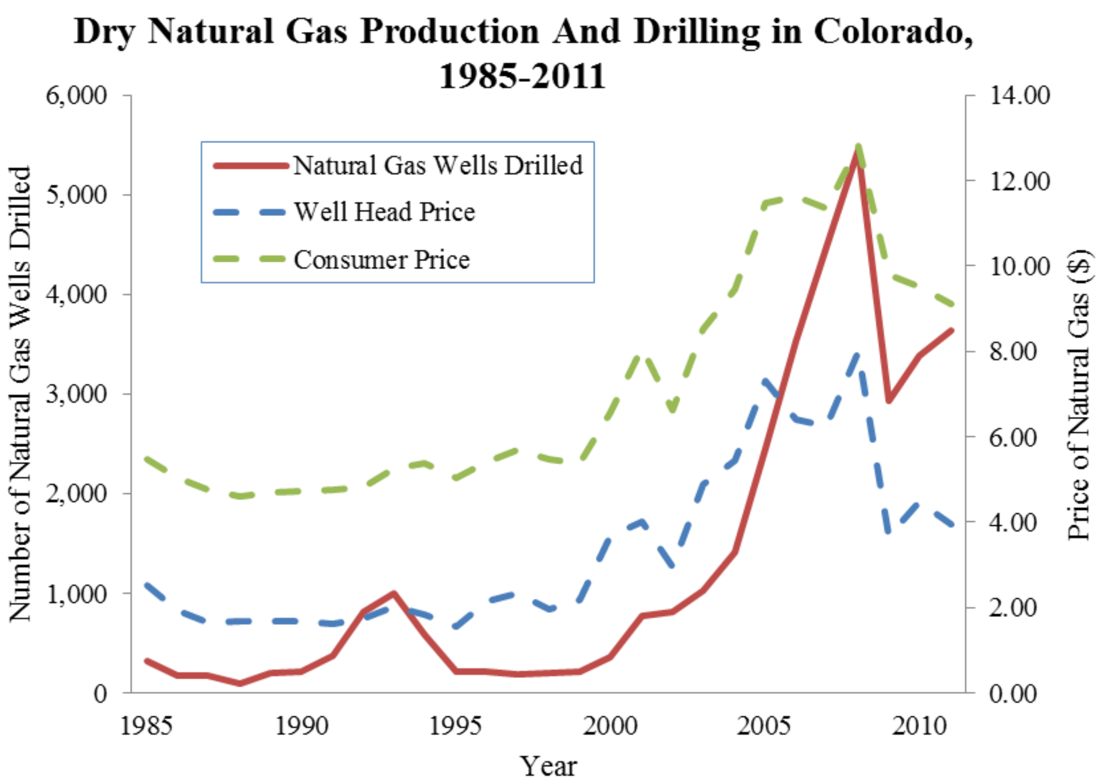
Source: Colorado Oil and Gas Conservation Commission (COGCC).

Figure 3.2: Total Natural Gas Wells and Production Over Time



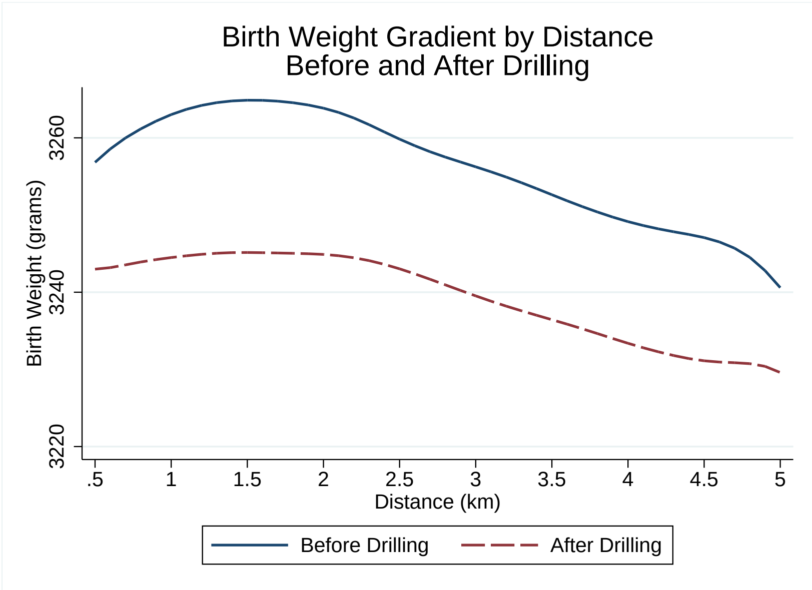
Source: Energy Information Administration (EIA) and COGCC.

Figure 3.3: Natural Gas Wells and Prices Over Time



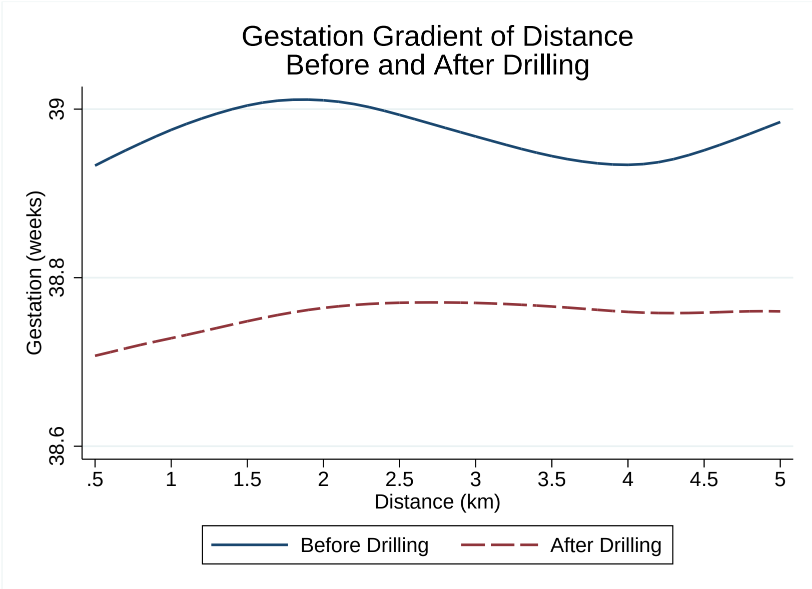
Source: EIA and COGCC.

Figure 3.4: Birth Weight Gradient of Distance from Closest Well



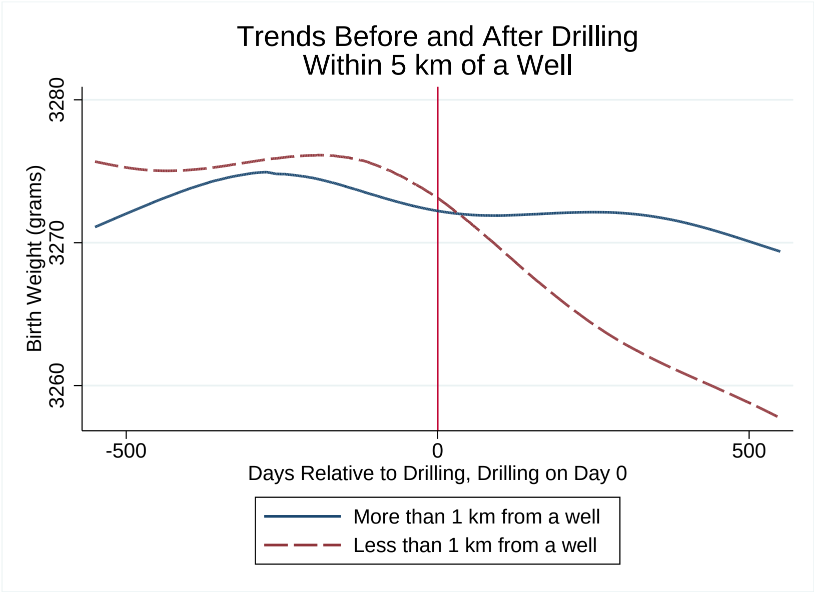
Note: Results from local polynomial regressions (bandwidth=0.1 km) of birth weight (grams) on distance from closest well's future/current location.

Figure 3.5: Gestation Gradient of Distance from Closest Well



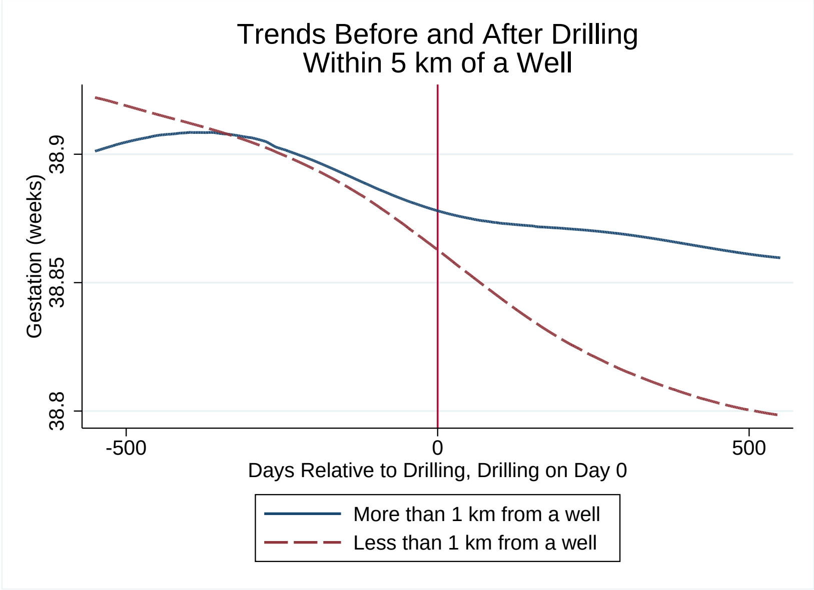
Note: Results from local polynomial regressions (bandwidth=0.1 km) of gestation (weeks) on distance from closest well's future/current location.

Figure 3.6: Birth weight Trends Within 5 km Before and After Drilling



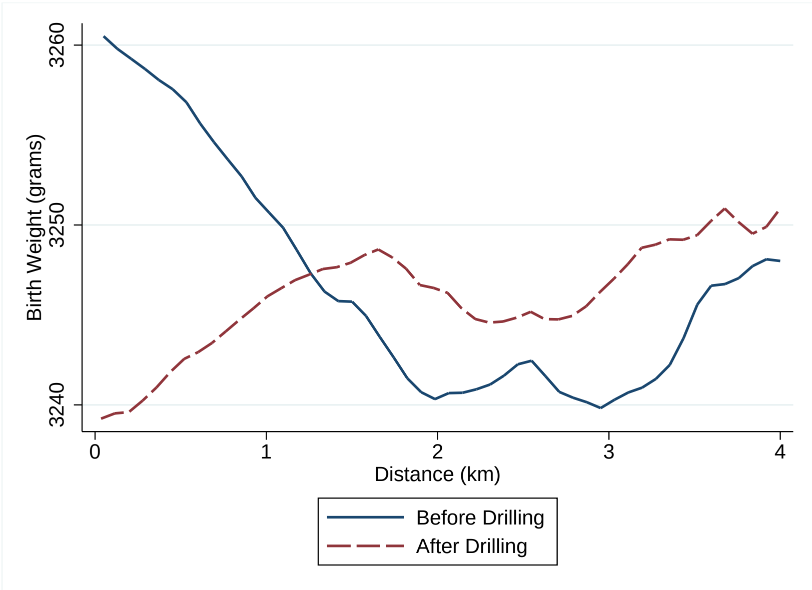
Note: Results from local polynomial regressions (bandwidth=90) of birth weight (grams) on days before/after spud date. Observations within 5 km of a well.

Figure 3.7: Gestation Trends Within 5 km Before and After Drilling



Note: Results from local polynomial regressions (bandwidth=90) of gestation (weeks) on days before/after spud date. Observations within 5 km of a well.

Figure 3.8: Birth Weight Residuals Over Distance



Note: Residuals have been added to the mean of birth weight.

Table 3.1: Characteristics of Births in Colorado, 2000-2011

	All Births	Residences within 5 km of well	
	Mean	Mean	Marginal effect in birth weight regression
Characteristics of birth			
Birth weight in grams	3221.96	3238.16	
Gestation in weeks	38.69	38.69	
Premature	0.089	0.088	
Low birth weight (LBW)	0.083	0.079	
Female	0.49	0.49	-115.5***
Mother's Characteristics			
Drop Out	0.22	0.19	
High School	0.25	0.24	-7.619
Some college	0.218	0.231	-11.59**
College plus	0.207	0.228	5.647
Teen Mom	0.064	0.058	
Mom Aged 19-24	0.28	0.26	54.36***
Mom Aged 25-34	0.52	0.54	85.09***
Mom Aged 35 and older	0.142	0.147	43.69***
Mom Black	0.030	0.011	-148.7***
Mom Hispanic	0.321	0.285	-42.06***
Smoked while pregnant	0.084	0.078	-171.7***
Married at time of birth	0.732	0.765	41.95***
Had a previous birth with a risk factor	0.238	0.239	-14.90
Parity	2.015	2.0	20.70***
Sample Size	815,760	158,428	64,081
R^2			0.042

* p<0.10, ** p<0.05, *** p<0.01

Table 3.2: Summary Statistics For Difference-in-Difference Sample

	Sample Means		T-Stat
	Within 1km	1-5 km	of Difference
Characteristics of Birth			
Birth weight	3299.98	3267.58	-4.09***
Gestation Length	38.86	38.80	-2.13*
Premature	0.065	0.074	2.43*
Low birth weight (LBW)	0.055	0.060	1.3
Very low birth weight (vLBW)	0.007	0.009	1.73
Female Child	0.48	0.49	2.37*
Mother's Demographic Characteristics			
Age	27.50	27.01	-5.38***
Education	13.59	13.26	-5.90***
White	0.955	0.924	-8.53***
Black	0.004	0.022	9.66***
Asian	0.016	0.021	2.24*
Other race	0.025	0.034	3.46***
Hispanic	0.306	0.347	5.77***
Smoked during pregnancy	0.067	0.089	5.45***
Married	0.770	0.736	-5.14***
Previous Risky Pregnancy	0.204	0.207	0.48
Parity	2.082	2.049	-1.91
Characteristics of Oil and Gas Wells near residence			
Average distance to closest well	0.61	2.55	137.90***
Number of wells drilled in year of birth	5.21	6.52	11.00***
Number of wells drilled within 5 km of residence	126.48	44.74	-74.70***
Sample Size	6448	14241	

* p<0.10, ** p<0.05, *** p<0.01

Table 3.3: Differences in Average Characteristics Close to Well Locations

	Characteristic of Mother					
	Teen Mom	High School Drop Out	Hispanic	Smoked	Married	Risky Pregnancy
	(1)	(2)	(3)	(4)	(5)	(6)
	Panel A: Pre-drilling differences in characteristiscs					
Within 1 km of well	-0.0260***	-0.0513**	-0.0446	-0.0106	0.0369	-0.00755
	(0.00549)	(0.0253)	(0.0341)	(0.00797)	(0.0247)	(0.0116)
Sample Size	15,705	15,705	15,705	15,705	15,705	15,705
R^2	0.028	0.133	0.190	0.044	0.046	0.200
	Panel B: Pre- and post- drilling differences using DD estimator					
Within 1 km * post-drilling	0.0262***	0.0227	0.00449	0.00170	-0.0140	-0.0116
	(0.00464)	(0.0182)	(0.0243)	(0.00715)	(0.0176)	(0.00846)
Sample Size	20,689	20,689	20,689	20,689	20,689	20,689
R^2	0.029	0.124	0.176	0.041	0.044	0.208

Note: Each coefficient is from a different regression. Pre-drilling (post-drilling) refers to births that occur before (after) the spud date of the closest well. Standard errors are clustered at the mother's residence zip code. The sample is limited to a four-year window surrounding drilling (i.e. 2 years prior and 2 years after), residences within 5 km of a well and singleton births. All regressions include quarter and year of birth, residence zip code, and quarter*year fixed effects. Source: Author calculations from Colorado Department of Public Health and Environment Vital Statistics.
* p<0.10, ** p<0.05, *** p<0.01

Table 3.4: Impact of Well Location on Birth Outcomes, 2000-2011

	Birth Weight		Gestation		Low Birth Weight		Premature	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	Panel A: Pre-drilling (5 km)							
Within 1 km of well	67.04***	52.29***	0.125***	0.127***	-0.0147*	-0.0114	-0.0264***	-0.0252***
	(10.91)	(11.24)	(0.0401)	(0.0354)	(0.00761)	(0.00744)	(0.00498)	(0.00488)
Sample Size	15,703	15,703	15,704	15,704	15,703	15,703	15,704	15,704
R^2	0.017	0.055	0.016	0.029	0.013	0.028	0.012	0.022
Maternal Characteristics	no	yes	no	yes	no	yes	no	yes
	Panel B: Pre- and post- drilling (5 km)							
Within 1 km * post-drilling	-38.89***	-35.79***	-0.108**	-0.114***	0.0180***	0.0170***	0.0216***	0.0215***
	(11.40)	(11.13)	(0.0421)	(0.0408)	(0.00564)	(0.00543)	(0.00443)	(0.00457)
Sample Size	20,687	20,687	20,687	20,687	20,687	20,687	20,687	20,687
R^2	0.014	0.055	0.014	0.025	0.011	0.025	0.011	0.021
Maternal Characteristics	no	yes	no	yes	no	yes	no	yes

Note: Each coefficient is from a different regression. Pre-drilling (post-drilling) refers to births that occur before (after) the spud date of the closest well. Standard errors are clustered at the mother's residence zip code. The sample is limited to a four-year window surrounding drilling (i.e. 2 years prior and 2 years after), residences within 5 km of a well and singleton births. All regressions include quarter and year of birth, residence zip code, and quarter*year fixed effects. Maternal characteristics include mother black, mother Hispanic, mother Asian, mother education (hs, some college, college), mother age (19-24,25-34, 35+), female child, smoking during pregnancy, drinking during pregancy, indicators for parity, indicator for previous/current risky birth and marital status. Source: Author calculations from Colorado Department of Public Health and Environment Vital Statistics.
* p<0.10, ** p<0.05, *** p<0.01

Table 3.5: Impact of Well Location on Levels of LBW and Prematurity

	Low birth weight			Prematurity (gestation)		
	2000-2500 grams	1500-2000 grams	<1500 grams	34-37 weeks	32-34 weeks	<32 weeks
	(1)	(2)	(3)	(4)	(5)	(6)
Within 1 km * post-drilling	0.0105***	0.000994	0.00286***	0.0126***	0.00285**	0.00507***
	(0.00262)	(0.00159)	(0.000953)	(0.00239)	(0.00114)	(0.000677)
Sample Size	20,689	20,689	20,689	20,689	20,689	20,689
R^2	0.053	0.034	0.040	0.043	0.033	0.030

Note: Each coefficient is from a different regression. Post-drilling refers to births that occur after the spud date of the closest well. Standard errors are clustered at the mother's residence county. The sample is limited to a four-year window surrounding drilling (i.e. 2 years prior and 2 years after), residences within 5 km of a well and singleton births. All regressions include maternal characteristics, quarter and year of birth, residence county, quarter*year, county*year and county*quarter*year fixed effects. See Table 3.4 for covariates included. Author calculations from Colorado Department of Public Health and Environment Vital Statistics.
* p<0.10, ** p<0.05, *** p<0.01

Table 3.6: Impact of Well Location on Maternal Health and Health Care

	Complication from Stress	Lung Disease	Labor Complications	Fetal Death (male/female ratio)	Large for Gestational Age	Prenatal Care
	(1)	(2)	(3)	(4)	(5)	(6)
Panel 1: Pre-drilling differences						
Within 1 km of well	-0.00526	0.000165	-0.0261**	-0.00600	0.0112**	0.0283*
	(0.00515)	(0.00344)	(0.0117)	(0.0130)	(0.00437)	(0.0161)
Sample Size	15,705	15,705	15,705	15,705	15,705	15,610
R^2	0.357	0.700	0.101	0.011	0.015	0.058
Panel 2: Pre- and post- drilling differences using DD estimator						
Within 1 km * post-drilling	0.0108**	-0.00392	0.00767	-0.0164**	-0.00474	0.00903
	(0.00439)	(0.00278)	(0.0162)	(0.00710)	(0.00313)	(0.00940)
Sample Size	20,689	20,689	20,689	20,689	20,689	20,576
R^2	0.395	0.723	0.128	0.039	0.037	0.060

Note: Each coefficient is from a different regression. Pre-drilling (post-drilling) refers to births that occur before (after) the spud date of the closest well. Standard errors are clustered at the mother's residence zip code. The sample is limited to a four-year window surrounding drilling (i.e. 2 years prior and 2 years after), residences within 5 km of a well and singleton births. All regressions include quarter and year of birth, residence zip code, and quarter*year fixed effects. Pre- and post-drilling regressions also include maternal characteristics. See Table 3.4 for covariates included. Author calculations from Colorado Department of Public Health and Environment Vital Statistics.

* p<0.10, ** p<0.05, *** p<0.01

Table 3.7: Impact of Well Location on Birth Outcomes by Gender

	Birth Weight		Gestation		Low Birth Weight		Premature	
	Females (1)	Males (2)	Females (3)	Males (4)	Females (5)	Males (6)	Females (7)	Males (8)
Within 1 km * post-drilling	-31.92*	-41.18**	-0.0896	-0.145**	0.0189**	0.0171	0.0302***	0.0136
	(19.16)	(20.16)	(0.0640)	(0.0717)	(0.00917)	(0.0105)	(0.00814)	(0.00916)
Sample Size	10,102	10,585	10,104	10,583	10,102	10,585	10,104	10,583
R^2	0.051	0.056	0.041	0.027	0.034	0.033	0.030	0.028

Note: Each coefficient is from a different regression. Post-drilling refers to births that occur after the spud date of the closest well. Standard errors are clustered at the mother's residence zip code. The sample is limited to a four-year window surrounding drilling (i.e. 2 years prior and 2 years after), residences within 5 km of a well and singleton births. All regressions include maternal characteristics, quarter and year of birth dummies, residence zip code dummies, and quarter*year fixed effects. See Table 3.4 for covariates included. Author calculations from Colorado Department of Public Health and Environment Vital Statistics.
* $p<0.10$, ** $p<0.05$, *** $p<0.01$

Table 3.8: Impact of Well Location on Birth Outcomes by Subgroups

	Birth Weight (1)	Gestation (2)	Low Birth Weight (3)	Premature (4)
Panel A: College plus only				
Within 1 km * post-drilling	-41.70	-0.0688	0.0135	0.0216
	(26.66)	(0.0992)	(0.00952)	(0.0149)
Sample Size	3,355	3,356	3,355	3,356
R^2	0.092	0.065	0.064	0.071
Panel B: Hispanic only				
Within 1 km * post-drilling	-9.605	0.00584	0.000878	-0.000983
	(23.96)	(0.0710)	(0.0138)	(0.0134)
Sample Size	6,908	6,907	6,908	6,907
R^2	0.056	0.043	0.037	0.036
Panel C: White non-Hispanic only				
Within 1 km * post-drilling	-45.49***	-0.168***	0.0249***	0.0312***
	(11.34)	(0.0581)	(0.00588)	(0.00478)
Sample Size	12,902	12,903	12,902	12,903
R^2	0.070	0.031	0.035	0.027
Panel D: Smokers only				
Within 1 km * post-drilling	-138.4**	-0.263	0.0573*	0.0415
	(61.00)	(0.180)	(0.0290)	(0.0321)
Sample Size	1,703	1,702	1,703	1,702
R^2	0.098	0.077	0.107	0.082
Panel E: 19-35 year olds mothers only				
Within 1 km * post-drilling	-46.65***	-0.134***	0.0215***	0.0225***
	(11.70)	(0.0468)	(0.00650)	(0.00428)
Sample Size	16,663	16,665	16,663	16,665
R^2	0.055	0.027	0.026	0.022
Panel F: Moms born in Colorado only				
Within 1 km * post-drilling	-35.69*	-0.284***	0.0209**	0.0345***
	(18.41)	(0.0802)	(0.00883)	(0.0123)
Sample Size	4,550	4,550	4,550	4,550
R^2	0.085	0.048	0.054	0.051

Note: Each coefficient is from a different regression. Post-drilling refers to births that occur after the spud date of the closest well. Standard errors are clustered at the mother's residence zip code. The sample is limited to a four-year window surrounding drilling (i.e. 2 years prior and 2 years after), residences within 5 km of a well and singleton births. All regressions include maternal characteristics, quarter and year of birth dummies, residence zip code dummies, and quarter*year fixed effects. See Table 3.4 for covariates included. Author calculations from Colorado Department of Public Health and Environment Vital Statistics.
* p<0.10, ** p<0.05, *** p<0.01

Table 3.9: Falsification Tests on Impact of Well Location

	Birth Weight	Gestation	Low Birth Weight	Premature	Birth Weight	Gestation	Low Birth Weight	Premature
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	Baseline Estimates				False Date 2 years before Spud Date			
Within 1 km * post-drilling	-35.79***	-0.114***	0.0170***	0.0215***	-3.813	-0.0544	0.000979	0.00724
	(11.13)	(0.0408)	(0.00543)	(0.00457)	(29.55)	(0.0890)	(0.00913)	(0.0136)
Sample Size	20,687	20,687	20,687	20,687	20,687	20,687	20,687	20,687
R^2	0.055	0.025	0.025	0.021	0.054	0.025	0.024	0.020
	Random date relative to spud date				Random date relative to birth date			
Within 1 km * post-drilling	6.659	-0.0768	0.00470	0.00520	13.90	-0.0641	0.00161	0.00905
	(16.73)	(0.0566)	(0.00656)	(0.00711)	(14.40)	(0.0470)	(0.00693)	(0.00695)
Sample Size	20,687	20,687	20,687	20,687	20,687	20,687	20,687	20,687
R^2	0.054	0.025	0.024	0.020	0.054	0.025	0.024	0.020

Note: Each coefficient is from a different regression. See Table 3.4. Author calculations from Colorado Department of Public Health and Environment Vital Statistics.
* $p<0.10$, ** $p<0.05$, *** $p<0.01$

CHAPTER 4
IMPACT OF SHALE GAS DEVELOPMENT ON AMBIENT AIR POLLUTION AND INFANT HEALTH IN TEXAS

4.1 Introduction

The last decade has experienced a rapid acceleration of shale gas production. This rapid increase has raised concerns about the potential impact of these operations on human health and the environment. A recent assessment by The Wall Street Journal estimates that over 15 million Americans live within 1 mile of an oil or gas well drilled since 2000 in 11 of the 33 states where drilling is taking place (Gold and McGinty, 2013). In the Barnett Shale in north-central Texas, these operations may occur in relatively close proximity to populated/urban areas, such as downtown Fort Worth.[1].

The Barnett Shale is uniquely suited for assessing potential community-wide exposures to air emissions from shale gas development. First, the Barnett Shale is the largest, oldest and most productive shale play in North America. It spans 24 counties, over 5,000 square miles and has over 15,000 active shale gas wells. Second, the Barnett Shale covers one of the larger metropolitan areas in the US, Dallas-Fort Worth and conveniently splits the two cities in half. For identification purposes, this is very advantageous as I can compare shale versus non-shale, with all of the drilling occurring on the western side and none occurring on the eastern side. This allows for the comparison of shale and non-shale areas that are all within the Dallas-Fort Worth regional economy and are based only on geological endowments alone. This allows for a clean identification strategy to estimate the effect of shale gas development on air emissions and infant health, separating it from other confounding factors. Third, due to the urban nature of this region, there is an extensive, and historical, air pollution monitoring network for the EPA's core criteria pollutants. And due to the growing concerns about shale gas development, the Texas

[1] Over 2,000 wells have been drilled to date within the city limits

Commission on Environmental Quality (TCEQ) established an extensive air monitoring network in the region. These unique data measure volatile organic compounds and other pollutants that are not generally measured, but are associated with shale gas operations. Fourth, it is one of the few urban areas with shale gas development, which is more often a rural phenomenon, and also a highly populated area. Given that this region has a history of strong economic activity, it is also an area that has high historical levels of ambient air pollution.

This paper provides the first analysis of the medium to long-term effect of shale gas development on ambient air emissions and infant health by looking at zip code level data from 1995-2008 in the Barnett Shale of Texas. My study period covers more than a decade of development including a period of rapid increase in the mid-2000s.

Using a difference in difference framework, I estimate the impact of shale gas development on birth outcomes and air pollution. I find adverse outcomes for birth weight, low birth weight, gestation and premature birth. I also estimate how an additional well impacts birth outcomes and find that an additional shale gas well is associated with a reduction in birth weight of about 3 grams, on average. For the ambient air pollution analysis, the pollutants measured are: benzene, ethyl benzene, formaldehyde, sulfur dioxide, ozone, toluene, mp-xylene, o-xylene and nitric oxide. Generally, the trend for all of these pollutants is reducing over time, where the peak emissions are from 1998-2001 (prior to the drilling up-tick). Preliminary results using a DD framework are mixed, but suggest increased emissions associated with shale wells for the following pollutants: NO_x, SO_2 and formaldehyde. Hazardous air pollutants, such as benzene, ethyl benzene, mp-xylene and toluene (BTEX), increase with the initial introduction of drilling (1998-2001) but do not persist. NO_x and SO_2, as well as other VOCs associated with shale gas mix to form ground level ozone. Interestingly, ozone increases in the shale region from 2009-2012, after an increase in the precursors for ozone and the peak of drilling activity (2005-2008).

I also estimate the relationship between these air pollutants and birth outcomes. NO_x and SO_2 had adverse impacts on gestation and premature birth. Ozone had mixed effects. I also look at six pollutants (BTEX and formaldehyde) that are specifically emitted by shale gas operations and find that all of them have an adverse impact on infant health. Most of these six pollutants have not been studied extensively with respect to the infant health impacts and therefore are of independent interest.

4.2 Background

Air Pollution and Shale Gas Development

All stages of shale gas development have the potential to produce hazardous air pollution emissions (EPA, 2000, 2010, 2011; Kargbo et al., 2010; Schmidt, 2011). Air pollution has become a more immediate concern following some recent studies in Colorado that discovered higher levels of volatile organic compounds (VOCs), methane and other hydrocarbons near drilling sites (McKenzie et al., 2012; Colborn et al., 2012; Gilman et al., 2013; Pétron et al., 2012). Other emissions associated with combustion include particulate matter, polycyclic aromatic hydrocarbons, sulfur oxides and nitrogen oxides (Colborn et al., 2012; EPA, 2008). To date, a full classification of all emissions during drilling and hydraulic fracturing does not to exist (Moore et al., 2014).

According to a recent review of the studies on air emissions from the drilling process, there are a number of pollutants that can be released throughout the life cycle. Preproduction, or the drilling phase, could emit methane, hazardous air pollutants such as BTEX, non-methane VOCs, NO_x, $PM_{2.5}$, H_2S, and silica (Moore et al., 2014). During the production phase, methane, BTEX and non-methane VOCs are released into the atmosphere. VOCs, NO_x and SO_x are precursors for ground level ozone (Moore et al., 2014). Two recent studies have measured the release of non-methane volatile organic compounds (NMVOCs) and found that oil and gas development in Utah and the Barnett Shale are releasing significant quantities into the atmosphere (Helmig et al., 2014; Zavala-Araiza et al., 2014). In contrast, despite the large quantity of VOC emissions, a recent study looking at the Barnett Shale region and volatile organic compounds in the air concluded that, although VOCs are detected 80 percent of the time, the levels at which they are detected do not pose significant risks to human health (Bunch et al., 2014). The authors focus on volatile organic compounds associated with shale gas development and do not measure other core criteria pollutants.

Air emissions inventories for many of the older shale plays are available, such as the Barnett Shale in Texas and the Denver-Julesburg Basin in Colorado (Armendariz, 2009; Bar-Ilan et al., 2008; CODPHE, 2009; Sage Environmental Consulting, 2011). Air emissions inventories indicate that the majority of emissions are of pollutants with low toxicities (e.g. methane, ethane, propane and butane), but several pollutants with high toxicities are also being emitted during the drilling process (i.e. benzene, acrolein and formaldehyde). The majority of air pollution detected is attributed to on-going production activities and compressor stations, suggesting that the air emissions persist beyond the introduction of drilling activities (Armendariz, 2009; Bar-Ilan et al., 2008; Pétron et al., 2012). For example, CODPHE (2009) indicates that ambient benzene and VOC levels increased by 38% and 40%, respectively, from 1996 and 2007 and are likely related to the large increase in shale gas development in Garfield County, Colorado. A study of Texas drilling rigs found that the total amount of combined organic compounds emitted for the year 2008 was 82,251 tons/year for all drilling activity that year.[2] However, a fairly comprehensive study in Fort Worth, Texas found that, despite detecting increased hazardous air pollutants associated with drilling, the 600 foot setback distance within the city for the

[2]This figure combines measurements for CO, NO_x, PM_{10}, SO_2 and VOCs (Eastern Research Group, 2009).

average exposure was protective of human health according to the air dispersion modeling performed (Sage Environmental Consulting, 2011). The authors recommended a longer-term monitoring program with greater scope to confirm their findings from air dispersion modeling.

An important recent study in Colorado, Colborn et al. (2012), measured air pollution continuously for one year near a well pad that was located in a sensitive area that required the operator to abide by best management practices designed to minimize impacts. Despite a closed-loop system used to pipe fracturing fluids to the pad and immediately capture the flow back fluids and pipe them to another facility for treatment, the study still measured non-methane hydrocarbons throughout the drilling and production phases. The authors also detected polycyclic aromatic hydrocarbons (PAHs) at greater concentrations within 1.1 km of the well pad than those at which prenatally exposed children in urban studies had lower developmental and IQ scores (Colborn et al., 2012).

In addition to the potential air pollution from the drilling process itself, traffic is often cited as a potential cause of increased ambient air pollution (Considine et al., 2011). According to a report to the New York Department of Environmental Conservation (NY DEC), the estimated quantity of traffic necessary for well completion is anywhere from 1,500 to over 2,000 truck trips (ALL Consulting, 2010). This traffic is necessary to haul in and out drilling fluids, sand and drilling equipment. Volatile organic compounds (VOCs), which include BTEX and other hydrocarbons, and fugitive methane gas mix with nitrogen oxides (NO_x) from truck exhaust and produce ground-level ozone (Gilman et al., 2013).

4.2.1 Literature Linking Air Pollution and Infant Health

The exact biological mechanisms through which air pollution impacts infant health are not yet well understood. However, in the last decade, the environmental health literature has grown with many studies linking air pollution and infant health outcomes. Table 4.1 lists selected recent works that study the infant health impacts of exposures to pollutants that have been linked to drilling activities. For example, a recent multi-country evaluation explored the heterogeneous impacts of maternal exposure to particulate matter (PM) and term birth weight and found in meta-analysis that increased exposure to PM10 reduced term birth weight by 8.9 grams on average (Dadvand et al., 2013). A few recent studies have linked exposure to polycyclic aromatic hydrocarbons (PAHs) during pregnancy with increased risk of intrauterine growth retardation (one cause of low birth weight), as well as both term and pre-term low birth weight (Dejmek et al., 2000; Vassilev et al., 2001; Perera et al., 2005). Benzene is one of the most commonly measured air pollutants associated with shale gas development and has been linked to a reduced birth weight of 58 grams, 66 grams and 77 grams in recent studies, respectively (Chen et al., 2000; Aguilera et al., 2009; Slama et al., 2009).

Stillerman et al. (2008) review the epidemiological literature and find associations between low birth weight and maternal exposures to PM, SO_2, CO, NO_x, VOCs and ozone. Most of the studies cited looked at these pollutants in isolation, but with shale gas development mothers are likely exposed to many at the same time and there is little research that examines any compounding effects.[3] Unfortunately, many of the epidemiological studies do not take into account socio-economic status and so the observed relationships could reflect unobserved factors that may be correlated with pollution and infant health outcomes (i.e. urban areas).

[3]See Currie et al. (2009); Shah and Balkhair (2011); Stieb et al. (2012); Glinianaia et al. (2004); Sram et al. (2005) for other reviews of past literature related to air pollution and birth outcomes.

There is a growing literature in environmental health economics that addresses the most common air pollutants utilizing quasi-experimental designs and rich controls for potential confounders to identify the infant health effects of ambient air pollution.[4] For example, Currie and Walker (2011) estimate that reductions in air pollution from E-Z Pass result in reductions of LBW between 8.5-11.3 percent and Currie et al. (2009) find that a one unit change in the mean level of carbon monoxide increases the risk of LBW by 8 percent. For comparison, Currie et al. (2009) find that mother's smoking in utero increases LBW by 0.18 percentage points or a 2% increase in the overall prevalence of LBW in New Jersey during their study period.

Zahran et al. (2012) utilize the natural experiment of benzene content in gasoline from 1996 to 1999 in the US and found exposure to benzene reduces birth weight by 16.5 g and increases the odds of a very low birth weight event by a multiplicative factor. Lavaine and Neidell (2013) use the natural experiment of a strike that effected oil refineries in France to explore the temporary reductions in SO_2 and find that the reductions increased birth weight by 75 grams, on average (2.3 percent increase) and reduced low birth weight by 2 percentage points for residences within 8 km of the air pollution monitor. However, they also detect longer gestational periods and calculate that almost all of the improvements in birth weight can be linked to increased gestational periods, rather than intrauterine growth restriction (IUGR).

Currie and Schmieder (2009) explore the Environmental Protection Agency's (EPA) Toxic Release Inventory (TRI) to look at some of the pollutants that are not commonly measured, such as toluene and fugitive volatile organic compounds (VOCs). These are mentioned with gravest concern in the public health literature addressing public health concerns associated with shale gas development (Witter et al., 2008; Korfmacher et al., 2013; Schmidt, 2011; Shonkoff, 2012). Currie and Schmieder (2009) find that a 2 standard

[4]See Currie et al. (2013c) for a review of the economics literature on short and long term impacts of early life exposure to pollution.

deviation increase in toluene increased low birth weight by 1.9 percent and find that exposure to VOCs reduced birth weight on average and increased low birth weight by 0.87 percent.[5]

Relying on this extensive literature exploring the relationship between infant health and air pollution to provide biological plausibility to the results that follow, I build on the previous literature by using the natural experiment of the introduction of shale gas wells, rich controls for confounding maternal characteristics, and homogenous groups of mothers to investigate the effects of shale gas development on infant health. Table 4.2 contains the expected relationships between exposures of the pollutants studied in this paper and birth outcomes. Most of the pollutants measured by the TCEQ have a relationship with low birth weight and premature birth in the literature.

4.3 Data

My analysis is based upon a data set acquired from the Texas Railroad Commission (TRC) that contains GIS information for all of the wells drilled in the state of Texas since 1900 through 2012. I include observations beginning in 1980 to define cumulative (historical) drilling in the analyses that follow. Each well is defined by a permit number and American Petroleum Institute (API) number. There is information about the permit date, the spud date (date drilling began), the total depth date, the date the well was plugged (if applicable) and the date that the permit expired (if the well was never drilled). From these data, I am able to define numbers of permits issued in each month over the study

[5] Agarwal et al. (2010) use the TRI to investigate the effects of TRI on infant mortality and find that carcinogenic air pollutants (i.e. BTEX) have the most adverse effects on infant mortality. They also find that non-carcinogenic/non-developmental/non-reproductive toxins have statistically significant effects on infant mortality. And when the authors control for air pollution, they find that toxics in the water have adverse effects on infant mortality.

period, the number of wells drilled in each month, as well as the cumulative numbers of permits and wells. I am also able to create a measure of drilling intensity that is the ratio of the total number of wells drilled over the total number of permits issued to identify hot spots (presumably areas where most of the permits become wells).

My second source of data are pollution data obtained from the Texas Commission on Environmental Quality (TCEQ) website.[6] The data contain daily pollution measures for core criteria pollutants: carbon monoxide (CO), ozone, particulate matter less than 10 micrometers (PM_{10}), nitrogen dioxide (NO_2), nitric oxide (NO_x), and sulfur dioxide (SO_2). The data also contain pollution measures (less than daily) for volatile organic compounds that are highly correlated with shale gas development: benzene, ethyl benzene, toluene, mp/o- xylene (BTEX) and formaldehyde. In order to obtain a zip code level measure, I first calculate the distance between the zip code geographic centroid and each monitor station. I then weight each station by one over its distance from the centroid. I use monitors within 20 miles of the centroid (similar to Knittel et al. (2011); Currie and Neidell (2005)). Weather data were obtained from the EPA AirData website and provide daily values for wind, temperature and precipitation for the entire study period.[7] The data also contain pressure, relative humidity (important for estimating mortality models) and dew point for the years 2001-2011.[8] Tables 4.3, 4.4, and 4.5 contain the average values for these variables over time.

My third source of data comes from vital statistics natality and mortality data from Texas for the years 1995 to 2008. These birth certificate records contain residential addresses geocoded to zip code (and census tract for 1995-2003). The vital statistics contain important maternal characteristics such as race, education, age, marital status, and

[6] `http://www.tceq.state.tx.us/`

[7] `http://aqsdr1.epa.gov/aqsweb/aqstmp/airdata/download_files.html`

[8] I run the models controlling for these additional factors to test sensitivity and find similar results. Results available upon request.

whether the mother smoked during her pregnancy. In the empirical analyses that follow, I control explicitly for these, as well as month of birth, year of birth, the interaction, and gender of the child.[9] I exclude multiple births in all analyses because plural births are more likely to have poor health at birth independent of exposures to environmental pollution.

I focus on term birth weight, gestation (weeks), low birth weight and premature birth as the primary outcomes of interest. Term birth weight is defined as birth weight for infants who reach full term at 37 weeks gestation. Gestation is measured in weeks of gestation. Low birth weight, defined as birth weight less than 2500 grams, and premature birth, defined as gestation length less than 37 weeks, are commonly used as a key indicators of infant health and have been shown to predict adult health and well-being.[10] Each of these outcomes has been previously examined in both the epidemiological and economics literature (e.g., Currie and Neidell (2005); Currie et al. (2011); Mattison et al. (2003); Glinianaia et al. (2004); Knittel et al. (2011); Currie et al. (2009); Currie and Walker (2011); Currie et al. (2013a)).

Table 4.6 provides summary statistics for the universe of births in Texas from 1995-2008. The first column reports characteristics of all births and the second column reports

[9] I also test whether drilling activity has affected these characteristics directly by changing fertility and/or the composition of families living near shale gas development and I find few economically significant changes.

[10] Oreopoulos et al. (2008) use twin and sibling fixed effects models on data from Manitoba, Canada that follows births through 18 years of age to show that birth weight (and other infant health measures) has a significant effect on both mortality within one year and mortality up to age 17. They also find that birth weight is a strong predictor of educational and labor force outcomes, such as high school completion and welfare take-up and length. These findings are similar to those of Black et al. (2007) who use data from Norway and find that birth weight has a significant effect on earnings, education, height and IQ at age 18. Johnson and Schoeni (2011) use national data from the US and find that low birth weight increases the probability of dropping out of high school by one-third, lowers labor force participation by 5 percentage points, and reduces earnings by almost 15 percent. More recently, Figlio et al. (2013) use linked birth and schooling records in Florida and find that birth weight has a significant impact on schooling outcomes for twin births.

characteristics of births for mothers' residences in the analysis region: the Dallas-Fort Worth Metro. Column (3) provides a decomposition of birth weight of residences for the entire state. The regression also includes month of birth, year of birth, and zip code of birth dummies to account for any secular time trend. These control variables are included in all my subsequent regression analyses, but, for simplicity, I do not report these coefficients in the tables below.

Table 4.7 provides summary statistics for the primary difference-in-difference (DD) analysis sample in the Dallas-Fort Worth Metro and shows how the shale versus nonshale region differs in observable characteristics in the cross-section.

4.3.1 Time Trends for Outcomes of Interest

Figure 3.1 shows a map of the Barnett Shale and the demarcation of the shale through the center of Dallas-Fort Worth, Texas. Figure 4.2 shows the trends in permits and shale gas wells drilled over time in the Barnett Shale, Texas. The average number of permits issued and wells drilled per year prior to 2000 was 400 and 285, respectively. After 2000, the average number of permits issued and wells drilled jumped to 2700 and 2400, respectively. That's a growth of six fold. The peak year of 2008 experienced 5,184 permits and 4,773 wells drilled.

Figure 4.3 shows the trend in birth outcomes over time for the shale and nonshale regions. For term birth weight and gestation, the trends for both regions is indicative of reduced infant health over time. The trends for low birth weight and premature birth are also increasing, suggesting reduced health at birth over time. All of these measures support the common trends assumption for using a difference-in-difference estimation strategy.

Figures 4.4, 4.5 and 4.6 show the trends in ambient air pollution over the analysis period. The pollution trends track fairly closely between the two regions for the core criteria pollutants (figure 4.4 and figure 4.6). The trends for most of these pollutants are negative, except for ozone, which is increasing.

4.4 Empirical Strategy

4.4.1 Defining Shale and Identification

This paper builds off of the identification strategy first implemented by Weber et al. (2014) to study the appreciation of housing prices across shale and nonshale zip codes. The authors defined shale as those zip codes that have more than 99 percent of their area on shale and nonshale zip codes as those that have less than 1 percent of their area on shale. For this paper, I also use the convenient demarcation of a shale region versus non-shale as defined by the geology of the Barnett Shale, but I limit the sample to those zip codes that have a well within 10 miles of the zip code centroid to ensure that the areas are more uniform and equal-distant to shale development.[11]

The primary threat to my identification is that west-side zip codes could have different trends in birth outcomes prior to drilling than east-side, or shale, zip codes. As can be observed in the graphs for the trends over time, it is clear that the shale zip codes have better birth outcomes prior to development. Another potential threat is that shocks to birth outcomes unrelated to drilling may have affected shale and nonshale zip codes differently.

[11] 95% of zip codes are within 10 miles of a gas well. I estimate the main results with the entire sample and the results are qualitatively similar. These results are available upon request.

4.4.2 Statistical Estimation Framework

4.4.3 Modeling Impact of Shale on Birth Outcomes and Air Pollution

First, I use a difference-in-differences model –in which zip codes off shale are used as a control for those on shale– to estimate the impact of shale gas development on birth outcomes and air pollution. Due to the ecological nature of studying these outcomes at the zip code level, this model captures the entire system of shale gas, not just the localized effects of individual drilling events.

The difference-in-difference specification takes the following form:

$$\begin{aligned} Outcome_i = \delta_0 + \delta_1 X_i + \delta_2 Shale_i + \delta_3 Period_i + \delta_4 Shale_i * Period_i \\ + \alpha_1 Y_i + \chi_1 Z_i + \epsilon_i \end{aligned} \tag{4.1}$$

Thus, the counterfactual change in infant health (air pollution) for a zip code on the Barnett Shale is estimated using births (air pollution) for a zip code in the same economic region that is not on the Barnett Shale. This model controls for unobserved variables that are time invariant and zip code specific. I calculate Huber-White standard errors clustered at the zip code, due to the potential for serial correlation within the same zip code over time. $Shale_i$ is a dummy variable that equals one if a zip code is a shale zip code based upon zip codes that are above the Barnett Shale and are within 10 miles of a drilled gas well (zero is defined as zip codes in the Dallas-Fort Worth region that are also within 10 miles of a drilled gas well).[12] The $Period_i$ variables divide the 1995-2008 study period into four periods: 1995-1998 (pre drilling); 1998-2000 (initial drilling); 2001-2003 (modest

[12] 95% of zip codes in the region meet the criteria for gas wells within 10 miles of the centroid of the zip code. I also estimate these results with the entire sample and the results are qualitatively similar.

drilling); 2004-2008 (drilling boom); 2009-2011 (modest drilling but peak production).[13] Y_i includes birth month, birth year and the interaction to capture seasonal effects (pollution and birth outcomes are strongly seasonal) as well as time trends. Z_i are zip code fixed effects to capture zip code specific unobservable characteristics that are time invariant.

The estimated impact of shale gas drilling on infant health is given by the vector δ_2 and is the difference-in-differences estimator. The vector X_i contains mother and child characteristics including indicators for whether the mother is African American, Hispanic, four mother education categories (less than high school (left out category), high school, some college, and college or more), mother age categories (teen mom, 19-24, 25-34 and 35+ (left out category)), indicators for smoking during pregnancy, drank alcohol during pregnancy, mother's marital status, an indicator for whether the mom had any prenatal care, parity, indicators for previous risky pregnancy and current risky pregnancy and an indicator for sex of the child. All of these variables are categorical and so to preserve sample size I control for missing values by including an additional "missing" category for each of the mother characteristics.

4.4.4 Modeling Impact of Air Pollution on Birth Outcomes

In order to examine the effect of pollution on infant health at birth, I restrict the sample to zip codes that have a shale gas well within 10 miles of the zip code centroid and estimate models of the following form:

$$\begin{aligned} Outcome_i = \delta_0 + \delta_1 X_i + \delta_0 Pollution_i + \delta_1 Weather_i \\ + \alpha_i Y_i + \chi_i Z_i + \epsilon_i \end{aligned} \tag{4.2}$$

[13] I only observe birth outcomes through 2008, but am able to observe air pollution measures through 2011.

The vector $Pollution_i$ contains measures of ambient pollution levels using the monitors that are closest to the mother's residential zip code centroid. In the main models, it is just a scalar measure of average pollution for the entire pregnancy. I construct these gestation levels during pregnancy by taking the average pollution measure over the pregnancy, so that δ_0 reflects the effect from a change in mean pollution levels for the trimester or pregnancy. $Weather_i$ represents daily average and total precipitation, daily average and max temperature, and wind averaged over the entire pregnancy.

A necessary condition to identify the impact of pollution is that the variation in a given infant's exposure is uncorrelated with other characteristics of the infant's family that could effect infant health. Unfortunately, the data used here does not allow me to test this condition as I do not observe siblings or multiple observations over time.

4.5 Estimation Results

4.5.1 The Impact of Shale Gas Development on Birth Outcomes

To test the validity of my research design, I estimate equation (4.4.3) to estimate the difference-in-difference estimator to see if there are any changes in mother characteristics after drilling began. In Appendix Table C.1, there are a few statistically significant changes in observed maternal characteristics over time: moms on shale are less likely to smoke and more likely to be high school drop outs than those off-shale over the same time frame. I control for maternal characteristics in all regressions reported.

The difference-in-difference model, reported in Table 4.8, allows us to look at the changes in birth outcomes over time as drilling progresses. The initial years show an increased prevalence of low birth weight and premature birth of 0.03 and 0.05 percentage points, respectively (5 and 6 percent increase from the mean, respectively) and reduced gestation, on average. As drilling progresses, there is no additional impact on premature birth, however, each subsequent period continues to have reduced gestation lengths, on average. Beginning in the period 2001-2004, term birth weight is reduced by about 20 grams and low birth weight increased by 0.06 percentage points (10 percent increase from the mean). By the peak years of development (2004-2008), only term birth weight and gestation have statistically significant relationships, with shale being associated with a reduced term birth weight of 20 grams and gestation reduced, on average.

I also estimate a model that looks at the impact of the number of wells on birth outcomes. Within the shale region there are over 15,000 active gas wells and the previous analysis is just capturing the average effect of being in this particular region. Table 4.9 presents the DD results for number of wells drilled and finds that an additional well is associated with reduced term birth weight of 3 grams, on average. An additional well in the initial drilling period (1998-2001) is associated with decreased gestation and increased prevalence of premature birth of 0.0008 percentage points (0.9 percent increase in premature birth attributable to each additional well), on average.

4.5.2 The Impact of Shale Gas Development on Ambient Air Pollution

I also estimate the impact of shale development on ambient air pollution over time in the Barnett Shale. Table 4.10 reports the cross-sectional difference and the DD estimates for the core criteria pollutants. In the cross-section, the shale region is associated with more ozone, less nitric oxide (NO_x) and less sulfur dioxide (SO_2). But then looking at the difference-in-difference estimates over time, shale is associated with an increase in NO_x for most of the periods observed (last period not statistically signicant with a negative sign).[14] SO_2 increases consistently until the moderate drilling and peak production period (2009-2011). The initial drilling phase is associated with the largest increase of SO_2 and a 65 percent increase relative to the mean over the first 10 years of development. NO_x and SO_2 are precursors for ozone and so it is interesting that there is less ozone in the shale area than the nonshale region until the latter period.

4.5.3 The Impact of Ambient Air Pollution on Birth Outcomes

The first two sections of results correspond to a clear conclusion: shale gas development has an impact on infant health and ambient air quality. Despite there being a wealth of studies looking at ambient air quality and birth outcomes, there are very few studies that have looked at volatile organic compounds and pollutants specifically associated with shale gas.

Table 4.12 contains the results for the gestation level pollution model. For each pollutant, I took the average of the daily pollution levels for the entire gestation period. NO_x exposure during pregnancy reduced gestation periods and slightly increased prematurity. Ozone does not have a statistically detectable impact on the birth outcomes investigated. Increased average exposure to SO_2 over the pregnancy reduces birth weight, increases low birth weight and reduced gestation on average.

Few of the volatile organic compounds associated with shale gas development have been studied in conjunction with birth outcomes. Table 4.13 contains the results for the gestation level volatile organic compounds model. Gestation level exposure to the BTEX chemicals reduced birth weights and gestation periods on average, increased the prevalence of low birth weight and premature birth. Gestational exposure to formaldehyde is

[14] The increase for NO_x is suggestive of a 73 percent increase relative to the mean for the initial years through the peak years of drilling.

associated with reduced gestation, on average.

4.5.4 Robustness Checks

As a robustness check, I look at the impact of having wells drilled within the zip code boundary, as opposed to the zip code being on shale (which may not be directly indicative of where drilling occurs). In Appendix table C.2, I present these results and find that having shale wells within the zip code is associated with reduced term birth weight and gestation, on average. There are no effects detected statistically for low birth weight or premature birth.

4.6 Discussion and Interpretation

There are five main findings in this paper. First, my results suggest that shale gas development can have adverse effects on the health of people living nearby, namely that of prenatal infants. Babies born of mothers who lived in zip codes on the Barnett Shale had adverse birth outcomes. Shale gas development increased the incidence of low birth weight and premature birth by 5 and 6 percent, respectively in the earliest years of development. Low birth weight increased by 10 percent for the mid-development years of 2001-2004. Furthermore, term birth weight was decreased by 20 grams on average for the years 2001-2008. Gestation was reduced over the entire time frame studied. These impacts are very similar in magnitude to those in other studies of air pollution and infant health (Zahran et al., 2012; Slama et al., 2009). Given the wealth of studies that identify a causal link between birth weights and long-run outcomes, these impacts are likely to persist throughout these children's lives (Johnson and Schoeni, 2011).

Second, my findings suggest that shale gas development can have a measurable impact on ambient air quality. Shale zip codes during the peak development period (2004-2008) experienced higher NO_x, SO_2, and formaldehyde. Shale zip codes during the moderate drilling and peak production period (2009-2011) experienced higher Ozone and formaldehyde. BTEX chemicals had the largest increase in the shale region during the initial drilling phase (1998-2001) but these increases do no persist.

Third, my findings indicate that the pollutants increased by shale gas development have a direct impact on health at birth outcomes. The pollutants studied had significant adverse effects on the four birth outcomes studied. These relationships are detected in gestation models. The impact of ambient air pollution on infant health is studied on average, but the effects could be more acute depending on how close the mother's residence is to shale gas development.

Fourth, while other studies of shale gas development have ruled out water pollution as a primary mechanism for infant health impacts, this study shows the direct link between shale gas, ambient air pollution and birth outcomes. These results suggest that requiring air pollution monitoring of drilling sites could assist researchers and public health officials in efforts to ascertain exposure pathways for residents living nearby and inform policies to mitigate any risks that are likely to be very localized.

Fifth, this study is consistent with studies in other contexts: rural Colorado and rural Pennsylvania (Chapters 2 and 3). Despite the Barnett Shale being in an urban metro, there are still detectable adverse impacts of shale gas development on both air quality and infant health.

4.6.1 Pollution Thresholds of Measured Impact on Birth Outcomes

The protection of human health is one of the primary motivations for environmental regulation around the world. Children are particularly vulnerable to environmental exposures because their bodily systems are still developing and they often spend more time outside than adults (Currie et al., 2013d). Early life health affects long-term outcomes including future health, human capital accumulation, labor force participation and earnings, as well as, inter-generational health (Almond and Currie, 2011). Thus, the marginal returns to regulations that protect children may be rather diffuse (affect many outcomes) and may be large.

The US Environmental Protection Agency, Agencey for Toxic Substances and Disease Registry (ATDSR) and state regulatory agencies have developed Minimal Risk Levels (MRLs) to predict and prevent health effects. MRLs are determined by both the dose and the duration of exposure.[15] The National Ambient Air Quality Standards (NAAQS) has defined regulations for 5 core criteria pollutants that are studied in this paper.[16] I measure the threshold at which each pollutant studied impacts birth outcomes by defining dummy variables for deciles, quintiles and tertiles of average pollution levels during pregnancy for each of the observations. Using the same model, covariates, fixed effects and clustered standard errors as equation (4.2), I replace the gestation level of pollution with these distributional dummies.

Table 4.14 contains the pollution levels at which there is a significant impact of that pollutant on each of the birth outcomes studied. In the fifth column, I also report the maximum level of average pollution during gestation to give a sense of the variation in measured pollution during pregnancy. The last three columns define the levels where these pollutants are regulated. For all of the pollutants that had adverse effects of birth

[15] `http://www.atsdr.cdc.gov/mrls/mrllist.asp#46tag`
[16] `http://www.epa.gov/air/criteria.html`

outcomes, the "threshold" at which the effect is statistically significant is less than the regulatory level. This means that despite historically low levels of pollution, there are still adverse impacts on infant health.[17] And although regulations will never be put in place such that there is a risk level of zero, it is important to consider even small adverse effects on early life health, given the potential for long-lasting impacts on human capital and labor market outcomes. These findings are consistent with other work by economists that find that despite the historically low levels of ambient air pollution, there are still measurable and economically significant impacts on infant health (Currie and Neidell, 2005; Currie et al., 2009; Knittel et al., 2011).

4.7 Conclusions

This study seeks to understand and quantify the impacts of shale gas development on infant health and ambient air quality. The chemicals used during drilling, cleaning drill rigs and hydraulic fracturing are linked to birth defects, cancer and reduced lung function, but there is little guidance from the scientific literature about the magnitude, time horizon or likelihood of these effects. Additionally, recent studies have shown an increase in air pollution associated with drilling, but little research has been done to assess how far these air pollutants can travel.

As a first step, I assembled a unique data set at the zip code level that contain ambient air pollution measures, weather measures and infant health outcomes. I define zip codes that are on the Barnett Shale as "shale" zip codes and those that are off the Barnett (eastern/Dallas side) as "nonshale." I examine the impacts of shale gas development on term birth weight, gestation, low birth weight and premature birth. I also examine the impacts

[17] Studies in the environmental health literature that look at trends in measured air pollution relative to these regulatory levels and conclude no impact on health, without measuring health, may be misguiding policy.

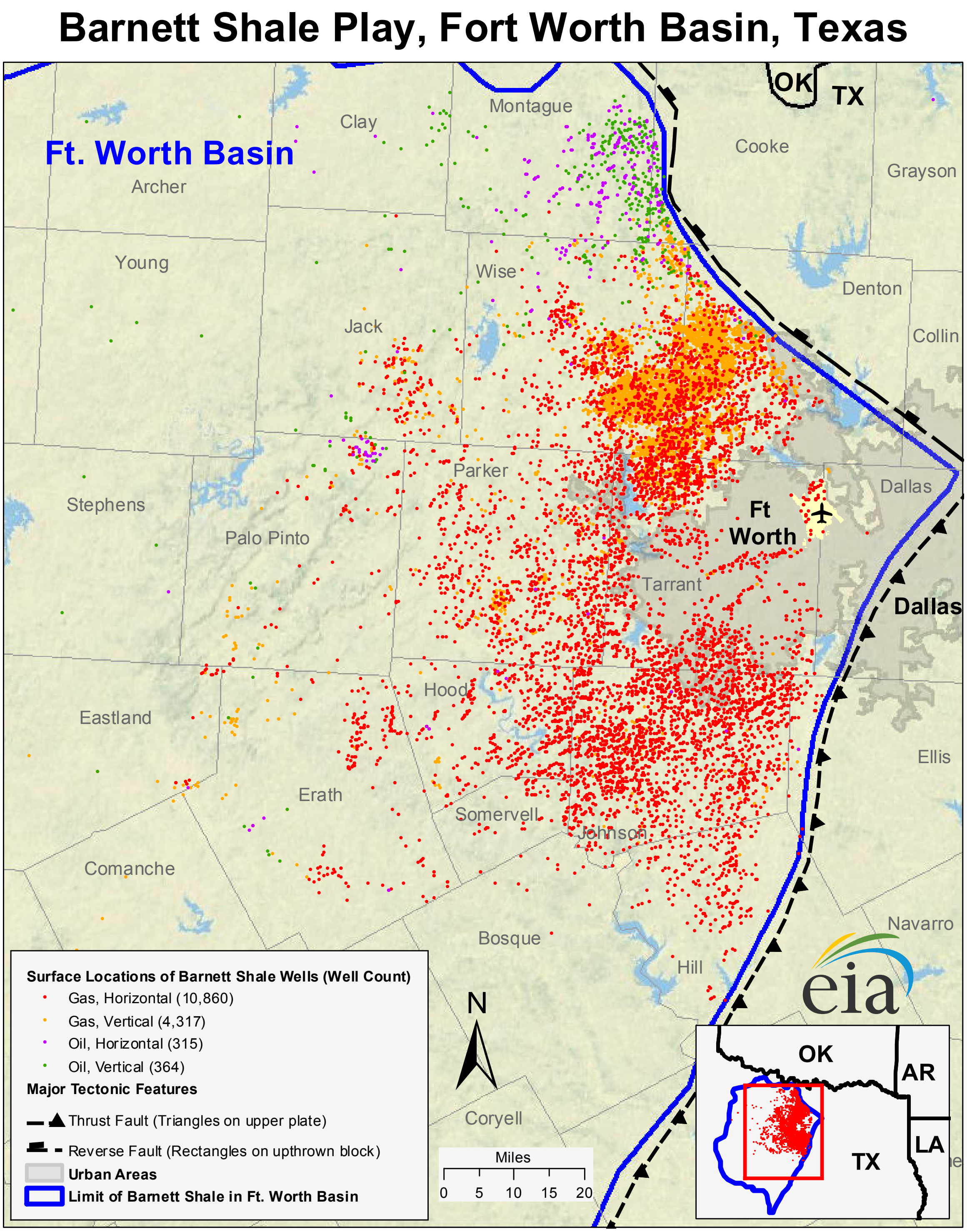
of shale gas development on eight air pollutants and the impacts of these same pollutants on infant health.

The results suggest that shale gas wells are associated with reduced average health at birth among infants born to mothers living in shale zip codes. There are also estimated relationships between shale development and increased air pollution. The results also point to direct adverse impacts of these same pollutants on infant health. The impacts associated with the specific pollutants studied in this paper are consistent with the estimates found in the epidemiological literature for air pollution impacts on low birth weight and term birth weight. The strength of this approach is in exploiting a natural experiment that controls for unobservable characteristics and the results are robust across a variety of specifications, providing evidence on the credibility of the research design.

It is clear from these results that policies intended to mitigate the risks of shale gas development can have significant health benefits. These findings add to the impetus for regulators to increase regulations that reduce air pollution emissions from drilling operations and for industry actors to increase voluntary action to reduce air pollution emissions.

While the research design does not allow for causal claims regarding all of the precise mechanisms of the effects of shale gas development on infant health, it does provide strong evidence that air pollution is a potential mechanism of concern. These findings indicate that air pollution pathways, and the nature and magnitude of their impacts, merit further investigation. In order to mitigate the potential risks, we need more guidance from scientific studies to show how far air emissions from gas operations are transported and/or the likelihood of surface and ground water contamination. Additionally, since I have focused on only the infant health effects of shale gas development, the total health effects of drilling exposure are likely to be much greater. Further research on the longer term health impacts of shale gas development on all members of our society is warranted.

Figure 4.1: Map of the Barnett Shale



Source: US Energy Information Administration based on data from HPDI, USGS, Pollastro et al (2007)
Updated: May 31, 2011

Figure 4.2: Drilling Over Time in the Barnett Shale

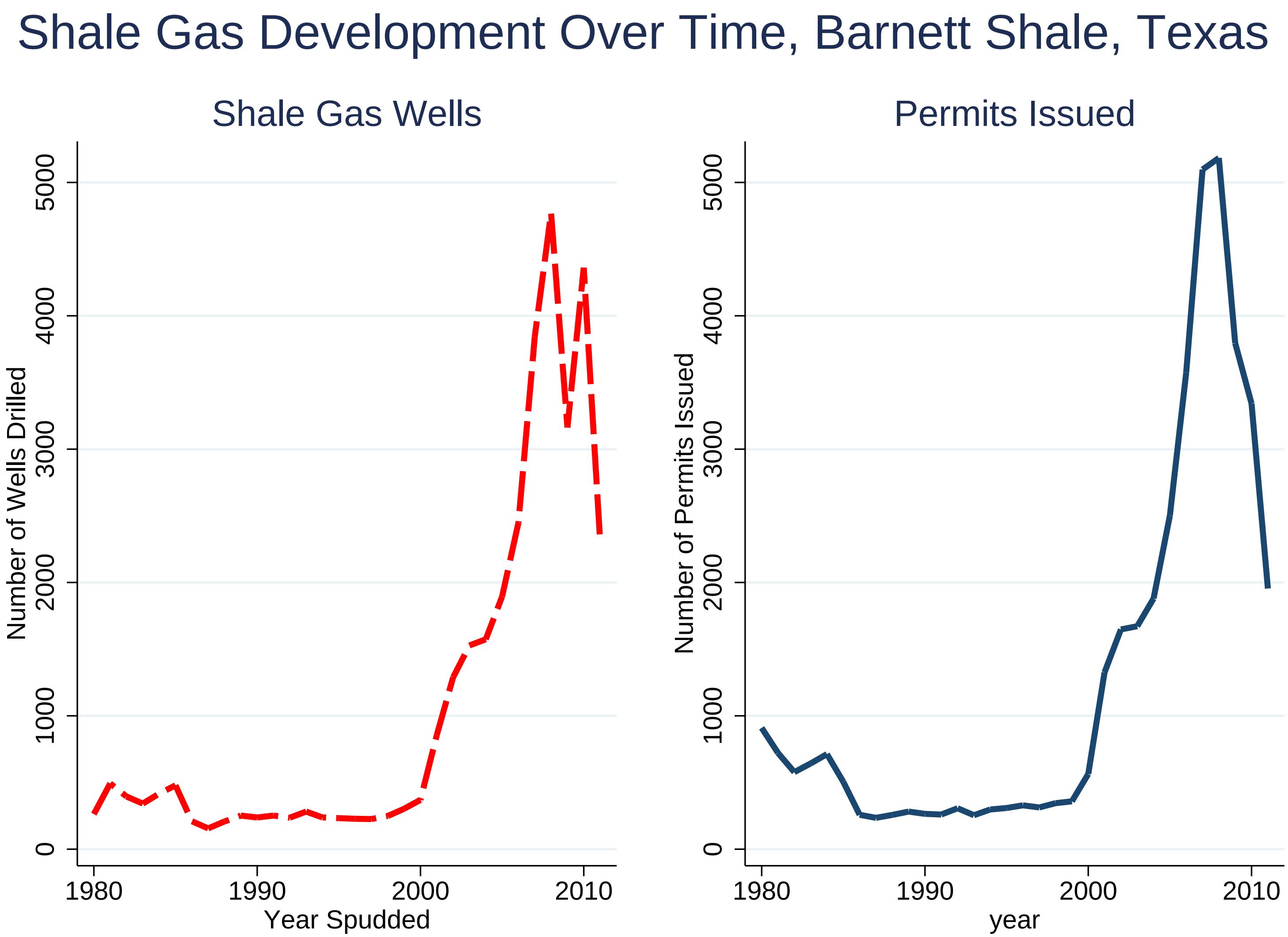


Figure 4.3: Trends in Birth Outcomes Over Time by Region

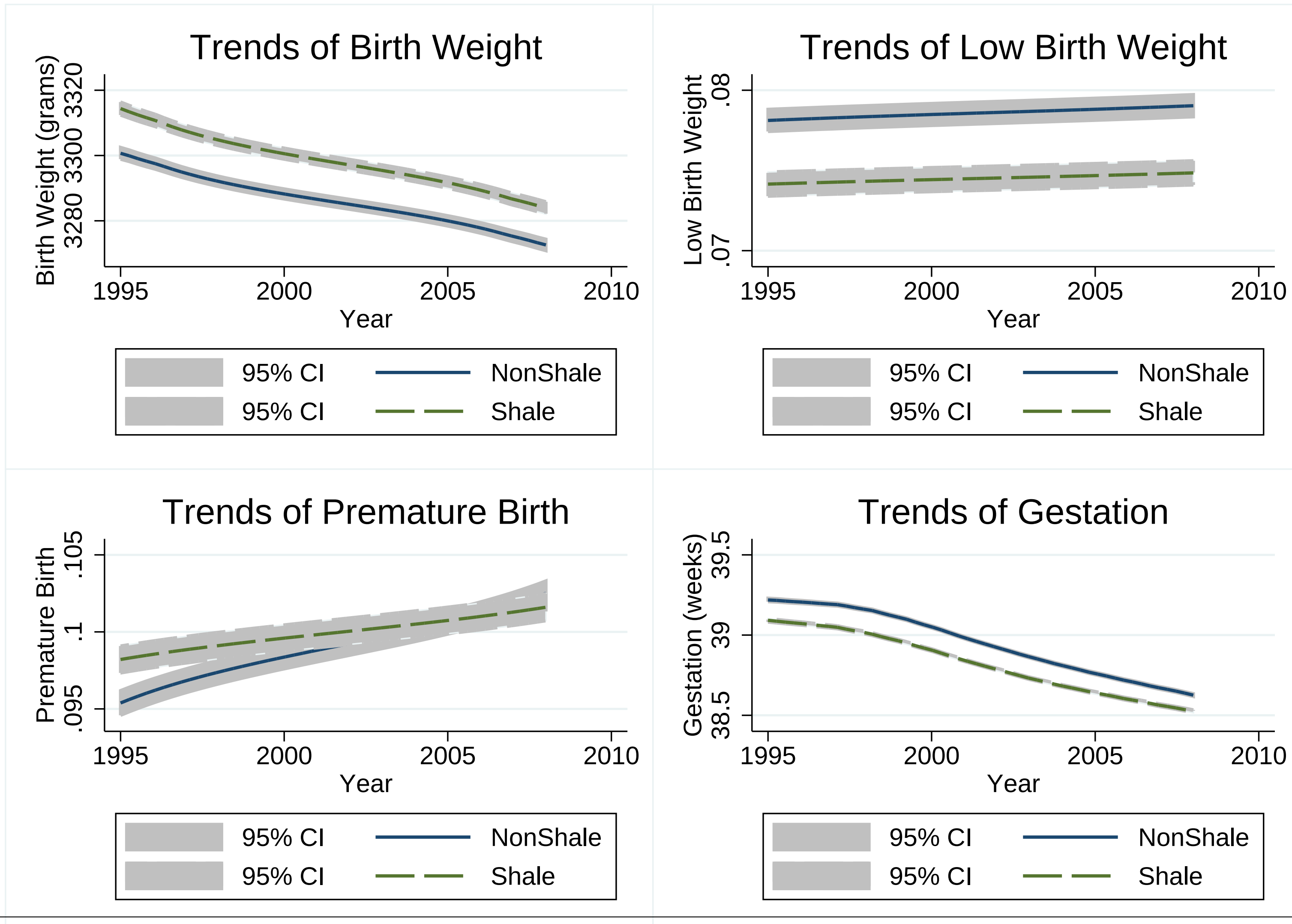


Figure 4.4: Trends in Core Criteria Pollutants Over Time by Region

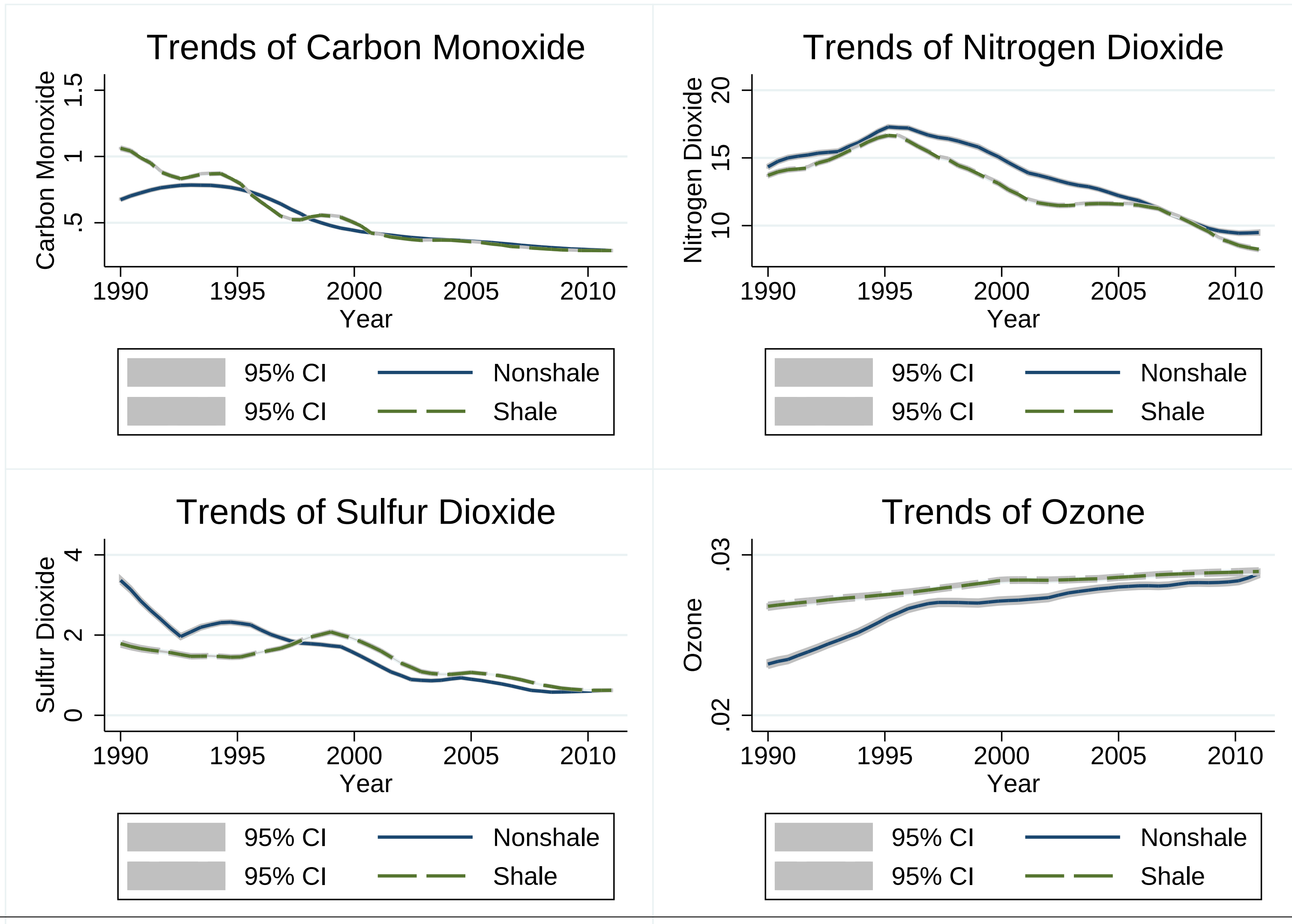


Figure 4.5: Trends in Volatile Organic Compounds Over Time by Region

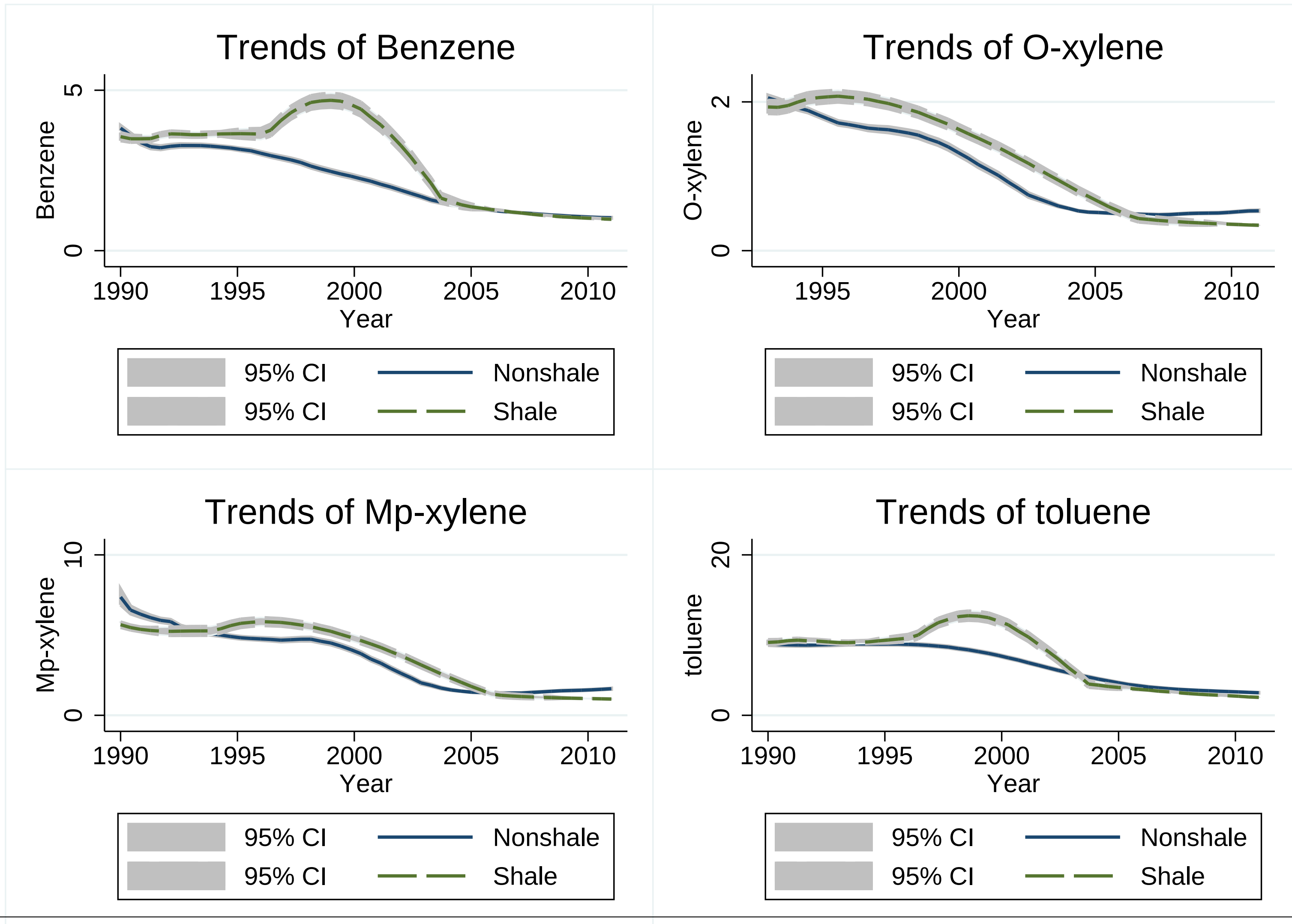


Figure 4.6: Trends in Air Pollutants Over Time by Region

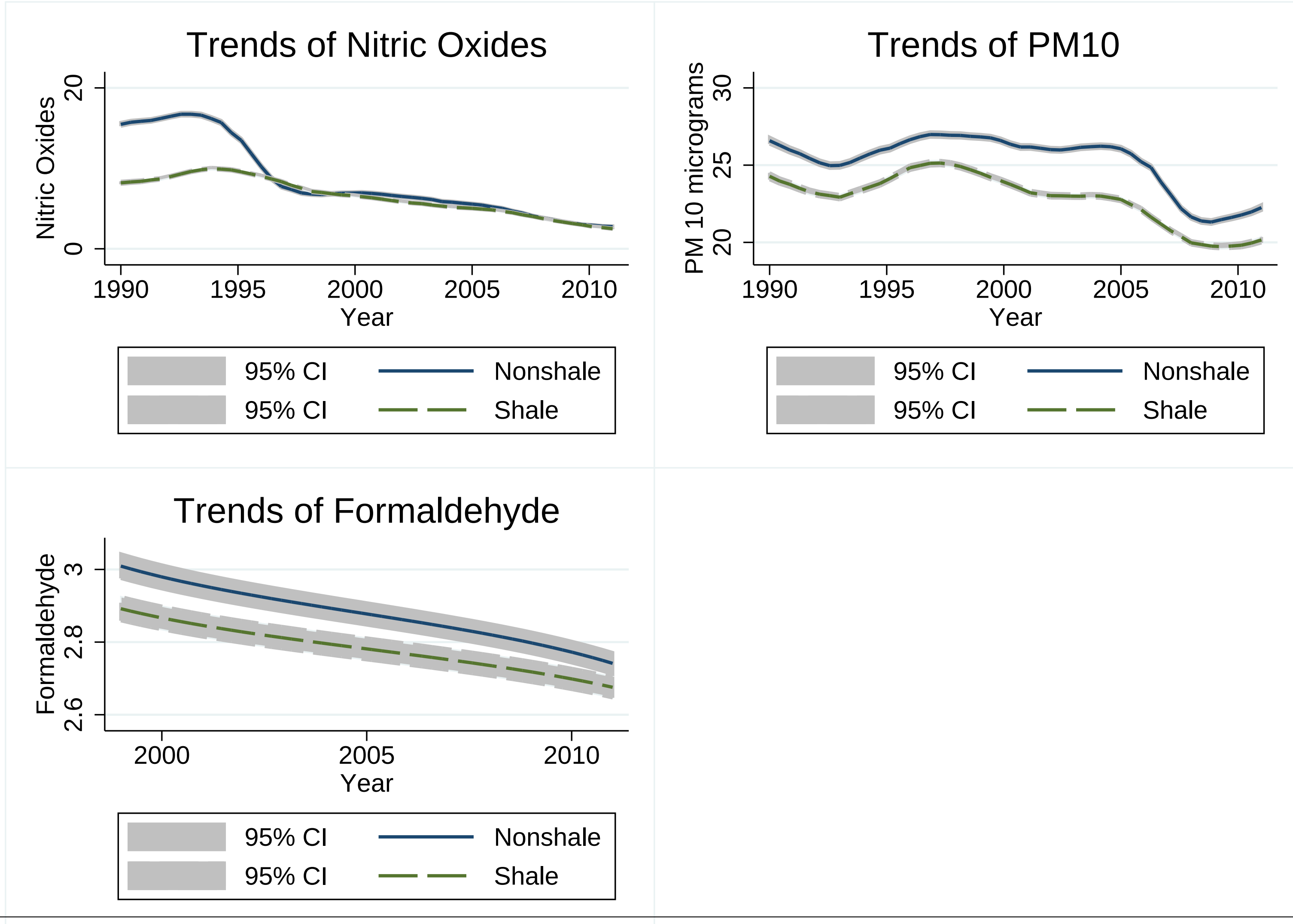


Table 4.1: Selected Studies Showing Effects of Environmental Air Pollution on Infant health

Pollutant	Study	Outcomes	Effects
CO	Currie et al. (2009)	LBW	1 unit change in CO increases LBW by 8%
		BW	1 unit change in CO reduces BW by 16.65g
NO2	Currie and Walker (2011) & NJ	LBW, premature	E-ZPass reduced LBW and prematurity by 10.8 and 11.8%
CO	Coneus and Spiess (2011)	BW	High exposure to CO leads to 289 g lower average BW
Particulates	Dadvand et al. (2013)	TBW	Increased exposure to PM reduced TBW (-8.9g)
PAHs	Dejmek et al. (2000)	IUGR	Associated with IUGR
	Vassilev et al. (2001)	TBW, LBW	Associated with LBW and TBW
	Perera et al. (2005)	BW, gestation	Associated with BW and gestation
Benzene	Chen et al. (2000)	BW	Benzene exposure reduced BW by 58g
	Aguilera et al. (2009)	BW	BTEX exposure reduced BW by 77g
	Slama et al. (2009)	BW	Benzene exposure reduced BW by 68g
	Zahran et al. (2012)	BW	Exposure to benzene reduced BW by 16.5g
		LBW	Increased odds of a very LBW infant
Toulene	Currie and Schmieder (2009)	LBW	2 sd increase in toulene increases LBW by 1.9%
VOCs		LBW, BW	Fugitive VOCs reduced birth weight and increased LBW by 0.87%
SO2	Lavaine and Neidell (2013)	BW, gestation	Reduced SO2 increased BW and gestation by 3% and 1.5%

Notes: BW= birth weight; LBW=low birth weight; TBW=term birth weight; PAHs=Polycyclic aromatic hydrocarbons.

Table 4.2: Hypotheses for Pollution Impacts on Birth Outcomes

Pollutant	Trimester Level: First	Trimester Level: Second	Trimester Level: Third	Pregnancy Level
NO_x				LBW
Ozone				BW, LBW
SO_2	LBW, preterm		LBW	
Benzene		BW, LBW	BW, LBW	BW, LBW, preterm
Ethyle Benzene		BW, LBW	LBW	BW, LBW
Toluene		BW, LBW	LBW	BW, LBW
Mp-xylene		BW, LBW	LBW	BW, LBW
O-xylene		BW, LBW	LBW	BW, LBW
Formaldehyde				LBW, preterm

Notes: BW= reduced birth weight; LBW= increased low birth weight; preterm= increased preterm. These hypotheses are formed from epidemiological studies. See Llop et al. (2010); Bell et al. (2007); Aguilera et al. (2009); Ghosh et al. (2012); Stieb et al. (2012); Laurent et al. (2013); Wilhelm et al. (2012); Gouveia et al. (2004); Bobak (2000); Salam et al. (2005); Duong et al. (2011); Lin et al. (2004) for these conclusions.

Table 4.3: Means and Standard Deviations for Core Criteria Pollutants

	CO	NO_2	NO_x	SO_2	Ozone	PM_{10}
1990	0.820087	13.00875	11.18203	4.082518	0.02614	27.52737
1991	0.761759	14.74829	13.00372	1.392464	0.023695	24.68579
1992	0.712781	15.62678	14.69483	2.128403	0.023515	23.61143
1993	0.807799	13.52586	12.35561	1.406467	0.023544	23.73378
1994	1.100073	16.40858	14.70544	2.213799	0.027193	23.63115
1995	0.82964	17.82942	12.98198	2.139194	0.028928	26.50726
1996	0.635142	16.87969	9.305819	1.842478	0.027733	27.05178
1997	0.493082	15.83237	6.794799	1.762475	0.02654	24.56
1998	0.525278	15.23732	6.342631	1.744261	0.027899	28.28768
1999	0.562164	15.85431	7.419038	2.023692	0.028696	25.35824
2000	0.417192	13.62359	5.920696	2.063371	0.027388	25.84969
2001	0.411349	12.49234	7.352124	1.482508	0.028025	24.61835
2002	0.35725	12.03278	5.4513	0.562197	0.027514	23.88913
2003	0.385475	11.96717	5.04183	1.001802	0.028848	26.03448
2004	0.374479	11.25868	5.128182	0.827133	0.027047	23.66563
2005	0.379813	11.80242	5.513157	1.127841	0.030288	26.23374
2006	0.333871	10.54574	4.045664	0.971462	0.031297	24.04535
2007	0.333843	10.6276	4.414542	0.722742	0.026093	21.36462
2008	0.311039	9.726311	3.574032	0.596255	0.028218	20.89923
2009	0.289987	8.562487	2.804233	0.51475	0.028721	18.14718
2010	0.279662	8.555746	2.245157	0.661992	0.028246	21.72448
2011	0.29123	8.240754	2.280828	0.630466	0.031213	22.46849
Total Mean	0.51828	12.7858	6.849939	1.441242	0.027642	24.36652
Overall SD	0.267668	4.322435	6.272412	1.341163	0.008313	6.476817

Source: Author calculations from Texas Commission on Environmental Quality data.

Table 4.4: Means and Standard Deviations for Volatile Organic Compounds

	Formaldehyde	Benzene	Ethyl Benzene	Mp-xylene	O-xylene	Toluene
1990	.	5.275	1.475	7.375	.	10.15
1991	.	.	.	.	.	.
1992	.	.	.	.	.	.
1993	.	3.240997	1.79143	5.827452	2.136988	9.191897
1994	.	3.081305	1.855257	5.765889	2.19076	8.477483
1995	.	4.119539	1.340482	3.936767	1.486823	8.444502
1996	.	3.089417	1.403149	4.61877	1.677868	8.532315
1997	.	3.132192	1.516101	5.041647	1.740074	10.41339
1998	.	2.967449	1.655522	5.899891	1.956944	10.52496
1999	7.9058	2.661721	1.327475	4.811849	1.572673	8.77963
2000	2.97179	5.673829	2.587341	8.344011	2.729806	16.03134
2001	1.872553	2.41466	0.8818622	2.975146	0.9978714	6.401347
2002	2.632444	1.787277	0.6915168	2.276772	0.7985214	5.162125
2003	2.983322	1.613083	0.5655718	1.599389	0.5839455	4.005081
2004	3.254103	1.424959	0.4443696	1.263484	0.4602756	3.599036
2005	3.486242	1.340615	0.4524241	1.325754	0.4688823	3.420441
2006	2.695772	1.241987	0.3448526	1.022854	0.3640276	2.907139
2007	2.234242	1.27332	0.4878367	1.401159	0.4977346	3.526308
2008	2.343699	1.084655	0.3733169	1.073732	0.3632089	2.52783
2009	2.238294	1.038007	0.407319	1.213481	0.4049406	2.467272
2010	2.638348	1.053797	0.4534102	1.451691	0.4409995	2.497872
2011	2.592843	0.9554278	0.347049	1.123841	0.3678667	1.977135
Total Mean	2.856982	2.210483	0.9574285	3.041235	1.068804	6.061504
Overall SD	1.902637	3.987163	1.925561	6.265553	2.064898	10.95991

Source: Author calculations from Texas Commission on Environmental Quality data.

Table 4.5: Means and Standard Deviations of Weather Variables

	Pressure	Relative Humidity	Dew Point	Wind	Temperature	Precipitation
1990	.	.	.	93.72231	19.00826	103.8918
1991	.	.	.	92.71241	18.38661	111.3804
1992	.	.	.	92.94452	18.16082	89.36431
1993	.	.	.	101.4085	17.76239	79.11911
1994	.	.	.	95.93631	18.32169	95.85714
1995	.	.	.	95.8722	18.45142	79.21612
1996	.	.	.	95.04031	18.52955	70.96197
1997	.	.	.	89.2298	17.94113	93.39083
1998	.	.	.	90.68279	19.8305	77.89922
1999	.	.	.	90.3547	19.57311	57.15797
2000	.	68.86431	49.58919	85.44445	18.88999	82.10057
2001	997.2218	68.3202	53.28566	85.27221	18.32093	83.53256
2002	997.6122	68.0185	52.6664	86.46039	18.10252	86.80098
2003	996.8549	66.17201	52.21382	88.96654	18.31567	57.63339
2004	997.5399	67.13296	53.36041	86.67764	18.45304	100.5327
2005	996.9442	57.94687	50.08108	89.51669	19.21292	41.23258
2006	996.7702	54.48637	49.15039	90.13041	19.99606	66.26538
2007	997.712	64.96817	52.17772	87.84288	18.50787	102.0492
2008	996.8724	57.55133	49.16255	89.35678	18.78779	62.83338
2009	996.7131	60.87841	50.26999	88.09273	18.58052	93.57306
2010	996.5755	60.119	50.39215	90.77496	18.75366	71.93575
2011	996.1687	54.97912	49.05313	92.31315	19.68707	53.55725
Total Mean	996.9899	62.06998	51.02972	90.73267	18.70789	80.01299
Overall SD	2.929555	8.254218	12.89896	11.56325	7.876639	55.22427

Source: Author calculations from EPA AirDAta.

Table 4.6: Characteristics of Births in Texas, 1995-2008

	All Births	Residences in Dallas-Fort Worth Metro	
	Mean	Mean	Marginal effect in birth weight regression
Characteristics of birth			
Birth weight (grams)	3273.90	3321.76	
Gestation in weeks	38.84	38.95	
Premature	0.11	0.086	
Low birth weight (LBW)	0.0765	0.061	
Female	0.489	0.488	-105.2***
			(0.577)
Mother's Characteristics			
Drop Out	0.37	0.344	-21.09***
			(1.469)
High School	0.274	0.263	-20.35***
			(1.023)
Some college	0.19	0.201	-11.87***
			(1.523)
College plus	0.166	0.192	
Teen Mom	0.0945	0.083	
Mom Aged 19-24	0.331	0.302	81.15
			(297.5)
Mom Aged 25-34	0.468	0.497	134.2
			(297.6)
Mom Aged 35 and older	0.106	0.118	130.8
			(297.6)
Mom Black	0.112	0.144	-189.2***
			(2.804)
Mom Hispanic	0.476	0.363	-8.557***
			(1.818)
Married at time of birth	0.652	0.657	52.69***
			(0.792)
Mom Smoked While Pregnant	0.225	0.041	-176.3***
			(1.685)
Previous Risky Pregnancy	0.0481	0.049	6.410***
			(2.113)
Currently Risky Pregnancy	0.119	0.119	-213.8***
			(2.287)
Sample Size	4580218	1164001	4,606,903
R^2			0.064

Source: Author calculations from Texas Department of State Health Services Vital Statistics. * p<0.10, ** p<0.05, *** p<0.01

Table 4.7: Summary Statistics For Difference-in-Difference Sample

	Sample Means	
	Non-Shale	Shale
Characteristics of Birth		
Birth weight	3315.04	3328.53
Gestation Length	39.01	38.90
Premature	0.09	0.08
Low birth weight (LBW)	0.063	0.058
Female	0.49	0.49
Mother's Demographic Characteristics		
Dropout	0.38	0.32
High School	0.26	0.27
Some college	0.80	0.81
College plus	0.22	0.24
Teen Mom	0.09	0.08
Mom Aged 19-24	0.31	0.30
Mom Aged 25-34	0.49	0.51
Mom Aged 35 and older	0.12	0.12
White	0.74	0.82
Black	0.17	0.11
Hispanic	0.45	0.30
Smoked during pregnancy	0.03	0.05
Married	0.62	0.69
Previous Risky Pregnancy	0.05	0.05
Currently Risky Pregnancy	0.13	0.11
Sample Size	565606	446382

Source: Author calculations from Texas Department of State Health Services Vital Statistics.

* p<0.10, ** p<0.05, *** p<0.01

Table 4.8: Impact of Well Location on Birth Outcomes

	Term Birth Weight (1)	Term Birth Weight (2)	Gestation (3)	Gestation (4)	Low Birth Weight (5)	Low Birth Weight (6)	Premature (7)	Premature (8)
shale	188.5***	191.7***	0.915***	0.877***	-0.0671***	-0.0617***	-0.0841***	-0.0774***
	(5.962)	(5.107)	(0.0184)	(0.0174)	(0.00149)	(0.00142)	(0.00168)	(0.00169)
years 1998_2001	-12.67	-14.22	-0.166***	-0.167***	0.00348	0.00308	-0.00197	-0.00282
	(10.57)	(10.07)	(0.0478)	(0.0469)	(0.00429)	(0.00423)	(0.00473)	(0.00467)
years 2001_2004	-30.63***	-36.40***	-0.332***	-0.326***	0.00740	0.00624	0.0213***	0.0207***
	(11.44)	(10.50)	(0.0563)	(0.0549)	(0.00468)	(0.00441)	(0.00523)	(0.00519)
years 2004_2008	-36.45***	-38.52	-0.984***	-0.809***	0.0116***	0.0252	0.0258***	0.0490***
	(10.72)	(32.84)	(0.0411)	(0.198)	(0.00438)	(0.0159)	(0.00461)	(0.0159)
shale * years 1998-2001	0.0783	-1.058	-0.130***	-0.131***	0.00267	0.00323*	0.00549**	0.00538**
	(4.451)	(4.168)	(0.0181)	(0.0186)	(0.00173)	(0.00171)	(0.00215)	(0.00214)
shale * years 2001-2004	-18.53***	-18.58***	-0.0823***	-0.107***	0.00329*	0.00616***	-0.00369*	-0.00246
	(5.657)	(4.690)	(0.0219)	(0.0218)	(0.00171)	(0.00168)	(0.00194)	(0.00192)
shale * years 2004-2008	-23.31***	-18.89***	-0.0452*	-0.0556***	0.000111	0.000203	-0.00409**	-0.00289
	(7.017)	(4.959)	(0.0235)	(0.0200)	(0.00188)	(0.00149)	(0.00201)	(0.00187)
Observations	925,817	925,817	955,481	955,481	1,012,418	1,012,418	1,012,373	1,012,373
R^2	0.008	0.061	0.023	0.052	0.003	0.037	0.004	0.026
Maternal Characteristics	no	yes	no	yes	no	yes	no	yes

Notes: Each coefficient is from a different regression. The sample is limited to singleton births. All regressions include indicators for month and year of birth, their interactions, and residence zip code indicators. Maternal characteristics include mother black, mother Hispanic, mother education (hs, some college, college), mother age (teen,19-24,25-34), female child, smoking and drinking alcohol during pregnancy, marital status, parity, previous risky pregnancy, current risky pregnancy, and prenatal care. Standard errors are in parentheses and clustered at the mother's residence zip code. Source: Author calculations from Texas Department of State Health Services Vital Statistics.
* p<0.10, ** p<0.05, *** p<0.01

Table 4.9: Impact of Number of Wells on Birth Outcomes

	Term Birth Weight (1)	Gestation (2)	Low Birth Weight (3)	Premature (4)
# wells	3.035***	0.00128	-0.000211	-0.000173
	(0.875)	(0.00380)	(0.000285)	(0.000383)
years 1998_2001	-14.20	-0.180***	0.00139	-0.00329
	(10.18)	(0.0454)	(0.00425)	(0.00467)
years 2001_2004	-35.20***	-0.358***	0.00738	0.0193***
	(10.59)	(0.0542)	(0.00447)	(0.00506)
years 2004_2008	-12.01	-0.779***	0.0168	0.0376**
	(33.75)	(0.191)	(0.0156)	(0.0158)
# wells * years 1998-2001	-0.676	-0.0113***	0.000309	0.000797*
	(0.891)	(0.00404)	(0.000336)	(0.000407)
# wells * years 2001-2004	-3.079***	-0.00169	0.000278	0.000102
	(0.861)	(0.00367)	(0.000276)	(0.000378)
# wells * years 2004-2008	-3.061***	-0.000767	0.000200	0.000153
	(0.870)	(0.00374)	(0.000280)	(0.000379)
Observations	951,573	983,504	1,040,364	1,040,313
R^2	0.061	0.054	0.037	0.026

Notes: Each coefficient is from a different regression. The sample is limited to singleton births. All regressions include indicators for month and year of birth, their interactions, and residence zip code indicators. Maternal characteristics include mother black, mother Hispanic, mother education (hs, some college, college), mother age (19-24,25-34, 35+), female child, smoking during pregnancy, marital status, parity, previous risky pregnancy, current risky pregnancy, and prenatal care. Standard errors are in parentheses and clustered at the mother's residence zip code. Source: Author calculations from Texas Department of State Health Services Vital Statistics and Texas Railroad Commission data.
* p<0.10, ** p<0.05, *** p<0.01

Table 4.10: The Impact of Shale on Ambient Air Pollution - Core Criteria Pollutants

	NO_x (1)	Ozone (2)	SO_2 (3)
Panel A: Cross-sectional difference			
shale	-2.455***	0.00582***	-0.243***
	(0.172)	(9.51e-05)	(0.00746)
Observations	58,839	67,137	55,445
R^2	0.801	0.952	0.716
Panel B: Differences in Pollution using DD estimator			
shale	-7.630***	0.00790***	-0.891***
	(0.358)	(0.000181)	(0.0397)
years 1998-2001	-6.678***	0.00218***	-5.500***
	(0.397)	(0.000304)	(0.172)
years 2001-2004	-8.536***	0.00382***	-5.364***
	(0.742)	(0.000512)	(0.174)
years 2004-2008	-10.61***	0.00682***	-5.122***
	(0.677)	(0.000459)	(0.195)
years 2009-2012	-4.089***	-0.000814***	-0.498***
	(0.181)	(0.000124)	(0.0351)
shale * years 1998-2001	5.854***	-0.00219***	1.145***
	(0.406)	(0.000214)	(0.0851)
shale * years 2001-2004	4.898***	-0.00183***	0.981***
	(0.415)	(0.000164)	(0.0636)
shale * years 2004-2008	5.443***	-0.00246***	0.937***
	(0.406)	(0.000177)	(0.0628)
shale * years 2009-2012	-0.00413	0.000114**	-0.170***
	(0.0812)	(5.47e-05)	(0.0307)
Observations	58,839	67,137	55,445
R^2	0.840	0.956	0.742

Notes: Each coefficient is from a different regression. Shale is an indicator for the zip code being on the Barnett Shale. All regressions include indicators for month and year of observation, their interactions and zip code indicators. Source: Author calculations from Texas Commission of Environmental Quality and Texas Railroad Commission data. Significance: * p<0.10, ** p<0.05, *** p<0.01

Table 4.11: The Impact of Shale on Ambient Air Pollution - Volatile Organic Compounds

	Benzene	Ethyl Benzene	Formaldehyde	Toluene	Mp-xylene	O-xylene
	(1)	(2)	(3)	(4)	(5)	(6)
			Panel A: Cross-sectional difference			
shale	0.141*	-0.273***	-0.0863***	-0.932***	-0.821***	-0.255***
	(0.0778)	(0.0372)	(0.000707)	(0.203)	(0.118)	(0.0395)
Observations	54,566	54,566	30,392	54,566	53,595	54,383
R^2	0.401	0.428	0.994	0.441	0.430	0.445
			Panel B: Differences in Pollution using DD estimator			
shale	0.301***	-0.224***	-0.143***	-1.105***	-0.565***	-0.180***
	(0.0946)	(0.0479)	(0.00391)	(0.279)	(0.153)	(0.0523)
years 1998-2001	-3.156***	-0.432***	3.068***	-3.768***	-4.023***	-2.243***
	(0.262)	(0.131)	(0.0126)	(0.713)	(0.414)	(0.0956)
years 2001-2004	-1.978***	0.198	0.0168***	0.291	-1.738***	-1.624***
	(0.347)	(0.198)	(0.00360)	(1.059)	(0.638)	(0.0781)
years 2004-2008	-2.358***	-0.00213		-1.420	-2.561***	-1.877***
	(0.335)	(0.201)		(1.079)	(0.653)	(0.0864)
years 2009-2012	-0.841***	-0.400***	1.483***	-2.222***	-0.998***	-0.349***
	(0.135)	(0.0572)	(0.00978)	(0.330)	(0.182)	(0.0615)
shale * years 1998-2001	2.493***	0.946***	0.126***	5.785***	2.539***	0.978***
	(0.227)	(0.106)	(0.00732)	(0.590)	(0.339)	(0.112)
shale * years 2001-2004	-0.176***	-0.156***	0.0740***	-1.012***	-0.726***	-0.208***
	(0.0411)	(0.0258)	(0.00505)	(0.135)	(0.0896)	(0.0297)
shale * years 2004-2008	-0.391***	-0.0133		0.0454	-0.0741	-0.0558
	(0.0702)	(0.0342)		(0.216)	(0.121)	(0.0386)
shale * years 2009-2012	-0.0832***	-0.154***	0.113***	-0.282***	-0.499***	-0.140***
	(0.0226)	(0.0157)	(0.00651)	(0.0717)	(0.0495)	(0.0158)
Observations	54,566	54,566	30,392	54,566	53,595	54,383
R^2	0.416	0.436	0.994	0.450	0.437	0.454

Notes: Each coefficient is from a different regression. Shale is an indicator for the zip code being on the Barnett Shale. All regressions include indicators for month and year of observation, their interactions and zip code indicators. Source: Author calculations from Texas Commission of Environmental Quality and Texas Railroad Commission data. Significance: * p<0.10, ** p<0.05, *** p<0.01.

Table 4.12: Effects of gestation level air pollution on birth outcomes- Core Criteria Pollutants

	NO_x (1)	Ozone (2)	SO_2 (3)
A. Models of birth weight			
Gestation Pollution	0.138	0.599	-5.546**
	(0.519)	(0.823)	(2.391)
Observations	937,160	1,007,223	944,548
R^2	0.068	0.069	0.070
B. Models of low birth weight			
Gestation Pollution	1.35e-05	0.00336	0.00147*
	(0.000167)	(0.00331)	(0.000775)
Observations	937,553	1,007,652	944,941
R^2	0.037	0.037	0.038
C. Models of Gestation			
Gestation Pollution	-0.00643**	-0.000119	-0.0345***
	(0.00265)	(0.000277)	(0.00946)
Observations	888,314	950,883	889,925
R^2	0.053	0.052	0.053
D. Models of prematurity			
Gestation Pollution	0.000630***	-4.06e-05	0.000240
	(0.000175)	(0.000283)	(0.000953)
Observations	937,509	1,007,607	944,903
R^2	0.026	0.026	0.026

Notes: Notes: Each coefficient is from a different regression. The sample is limited to singleton births and zip code centroids within 10 miles of a Barnett Shale gas well. Pollution measures are the average level of pollution for the entire pregnancy. All regressions include indicators for month and year of birth, their interactions, and residence zip code indicators. All regressions include maternal characteristics: mother black, mother Hispanic, mother education (hs, some college, college), mother age (19-24,25-34, 35+), female child, smoking during pregnancy, marital status, parity, previous risky pregnancy, current risky pregnancy, and prenatal care. Standard errors are in parentheses and clustered at the mother's residence zip code. Source: Author calculations from Texas Department of State Health Services Vital Statistics and Texas Commission of Environmental Quality air pollution measures.
Significance: * p<0.10, ** p<0.05, *** p<0.01

Table 4.13: Effects of gestation level air pollution on birth outcomes- VOCs

	Benzene (1)	Ethyl Benzene (2)	Formaldehyde (3)	Toluene (4)	mp-xylene (5)	o-xylene (6)
			A. Models of birth weight			
Gestation Pollution	-0.906*	-2.640**	-8.147	-0.267	-0.864**	-2.286**
	(0.483)	(1.262)	(6.884)	(0.228)	(0.382)	(1.134)
Observations	999,496	999,496	657,855	999,496	999,496	999,496
R^2	0.069	0.069	0.065	0.069	0.069	0.069
			B. Models of low birth weight			
Gestation Pollution	0.000601***	0.00115**	0.00475	0.000146	0.000323*	0.00106**
	(0.000202)	(0.000564)	(0.00297)	(9.87e-05)	(0.000179)	(0.000511)
Observations	999,923	999,923	658,094	999,923	999,923	999,923
R^2	0.037	0.037	0.036	0.037	0.037	0.037
			C. Models of Gestation			
Gestation Pollution	-0.0152***	-0.0341***	-0.0730**	-0.00495***	-0.00970***	-0.0314***
	(0.00279)	(0.00716)	(0.0349)	(0.00118)	(0.00211)	(0.00641)
Observations	943,312	943,312	630,918	943,312	943,312	943,312
R^2	0.052	0.052	0.052	0.052	0.052	0.052
			D. Models of prematurity			
Gestation Pollution	0.00169***	0.00392***	0.00492	0.000651***	0.00118***	0.00364***
	(0.000331)	(0.000810)	(0.00391)	(0.000134)	(0.000241)	(0.000723)
Observations	999,879	999,879	658,051	999,879	999,879	999,879
R^2	0.026	0.026	0.026	0.026	0.026	0.026

Notes: Notes: Each coefficient is from a different regression. The sample is limited to singleton births and zip code centroids within 10 miles of a Barnett Shale gas well. Pollution measures are the average level of pollution for the entire pregnancy. All regressions include indicators for month and year of birth, their interactions, and residence zip code indicators. All regressions include maternal characteristics: mother black, mother Hispanic, mother education (hs, some college, college), mother age (19-24,25-34, 35+), female child, smoking during pregnancy, marital status, parity, previous risky pregnancy, current risky pregnancy, and prenatal care. Standard errors are in parentheses and clustered at the mother's residence zip code. Source: Author calculations from Texas Department of State Health Services Vital Statistics and Texas Commission of Environmental Quality air pollution measures.
Significance: * p<0.10, ** p<0.05, *** p<0.01

Table 4.14: Impact of Average Level of Pollution over Gestation on Birth Outcome

	Threshold of Average Pollution During Pregnancy							
Pollutant	Birth Weight	Gestation	Low Birth Weight	Premature	Max Measured	EPA Acute MRL	EPA Chronic MRL	NAAQS (8 hour)
Benzene	0.0008	0.0018	0.0026	0.0018	0.0432	0.009	0.003	n.a.
E-Benzene	0.0002	0.0013	0.0005	0.0005	0.0178	5	0.06	n.a.
Formaldehyde	0.0025	0.0023	0.003	0.0033	0.0123	0.04	0.008	n.a.
Toluene	n.e.	0.0084	n.e.	0.0084	1.019	1	0.08	n.a.
Mp-xylene	0.0004	0.0057	0.0019	0.0014	0.055	2	0.05	n.a.
O-xylene	0.0001	0.0015	0.0007	0.0005	0.018	2	0.05	n.a.
CO	0.5	0.5	0.5	0.285	1.5	n.a.	n.a.	9
Nox	n.e.	n.e.	n.e.	0.045	33.4	n.a.	n.a.	25
Ozone	n.e.	n.e.	0.025	n.e.	0.072	n.a.	n.a.	0.075
SO2	0.0007	0.0005	0.0007	0.0007	0.0058	0.01	n.a.	0.5
PM10 (μ/g)	n.e.	23	n.e.	n.e.	43	n.a.	n.a.	150

Notes: Each "threshold" was calculated using deciles of average pollution during gestation and is defined at the level of pollution where there is a statistically signficant (and persistently statistically significant) impact on the outcome of interest. All regressions contain zip code fixed effects, month and year fixed effects and their interactions. Maternal characteristics are included and standard errors were clustered at the zip code level.
n.e. = no detected effect at levels measured; MRL = Minimum Risk Level as defined by the US EPA; NAAQS= National Ambient Air Quality Standards

APPENDIX A
APPENDIX TO CHAPTER 2: PENNSYLVANIA

A.1 Changes in Community Composition

Changes in community composition associated with shale gas development is one of the primary threats to using a difference-in-difference approach in a repeated cross-sectional framework used in this paper. Changes in community characteristics are primarily caused by migration in and out of communities with development activities. There are multiple reasons why families might move in response to drilling. For example, due to increased local economic activity in these communities, it is possible that families move into these communities to benefit from the improved economic conditions. If those who move towards improved economic activity have better (worse) health, then this would improve (reduce) the average health in the community. Alternatively, mothers who value their children's health may be more likely to move away from communities where drilling is taking place. This migratory effect would lower the average health of the observed births. However, it is also possible that those who are more likely to move away are families who are experiencing the worse health effects of drilling. This migratory effect would increase the average health of the observed births. Another form of migration may stem from the influx of workers entering these communities, but existing evidence suggests that greater shale gas production does not result in a less educated population (Weber, 2013; Muehlenbachs et al., 2014). Thus, it is not clear whether selection or composition of the mother characteristics would lead me to overestimate or underestimate the health impacts of close proximity to drilling activity.This issue is present in all empirical work using vital statistics, where each birth occurs only once.

I do not find any evidence of changes in the average demographics of mothers living near wells after drilling or in the probability that they move during the observed period.

This, however, could mask heterogeneity in the responses across mothers. Following Currie et al. (2013b), I use the sample of mothers who had multiple births during 2003-2010 to define whether the mother moved at any point during the time frame. I do not find a systematic relationship between low SES factors and the likelihood of moving. For example, I find that the least educated (high school or less) and smokers are more likely to move in response to drilling and that college educated mothers, African American mothers and teen mothers are less likely to move.[1] I do not find a statistically significant difference in the incidence of movers amongst Medicaid recipients, WIC recipients or those who have private insurance. Moms who were born in Pennsylvania are more likely to move after drilling.[2]

Muehlenbachs et al. (2014) use Census tract level data to investigate changes in neighborhood composition associated with shale gas development. Using 33 tract level attributes, they estimate the effect of the number of wellbores within 20 km of the centroid of the census tract on changes in neighborhood compositional changes from 2000 to 2012. The find very few economically significant effects, with no one attribute changing more than 1% over the 12 year period. They find a slightly smaller population and a slightly smaller per capita income, but no changes in education or other factors that are correlated with infant health. The authors conclude that any changes in neighborhood composition induced by shale gas development are quite small. These findings support my claims that changes in community composition is not likely to explain the results in this paper.

[1] Muehlenbachs et al. (2014) find increases in housing prices, on average. This may force lower socio-economic groups to move out of these communities.

[2] Results available upon request.

A.2 Discussion of Mechanisms

The research design used in this paper does not depend on a clear mechanism of exposure for the findings to provide defensible estimates of the effects of drilling on infant health. This is advantageous given the controversy regarding potential mechanisms and levels of exposure. However, some consensus is forming in the literature about the potential risks, their probabilities and which mechanisms of pollution exposure most fully explain my results.

To assist in facilitating the conversation regarding risk mitigation priorities, Krupnick et al. (2013) surveyed 215 experts in government, industry, universities and nongovernmental organizations to identify priority environmental risks related to shale gas development. The experts had a high degree of consensus about the specific risks to mitigate. Sources of surface water contamination were linked to site preparation, storage of fracturing fluids, on-site pits for storing flow back and produced water and treatment of flow back water. Ground water contamination was linked to flow back water storage, but was considered unlikely and required a long time horizon. Air quality concerns were linked to venting of methane during both the drilling and hydraulic fracturing phases. Experts identified surface water impacts to lakes, rivers and streams as the most dominant concern for ecological health. Other risks identified were related to road and well pad construction, pipelines and leaky casing/cementing.

Even if ground water contamination is more widespread than has been currently estimated, a growing area of the economics literature suggests that avoidance behavior may affect the measurement of the impacts of pollution.[3] People move away from polluted areas, stay indoors when there are ozone warnings and drink bottled water to avoid chemical contamination in public water drinking sources (Currie, 2011; Gamper-Rabindran and

[3]Well casing failure is estimated to be 6% of new wells drilled in 2010 in Pennsylvania Ingraffea (2012) or 90 well failures in 2010.

Timmins, 2011; Neidell, 2004; Graff Zivin and Neidell, 2009; Graff Zivin et al., 2011). The environmental health literature has very few studies that measure drinking water contamination effects on fetal health. A recent study found little effects, on average, of water contamination in NJ on low birth weight or premature birth (Currie et al., 2013b). The study did find statistically significant impacts on the least educated mothers and may be suggestive of avoidance behavior or other unobserved factors driving these differences. Given that most attention has been paid to ground water contamination in the media, individuals close to drilling sites are more likely to be aware and mitigate risks associated with water rather than air exposures. Muehlenbachs et al. (2014) find that housing prices are responsive to perceptions of groundwater contamination risk in Pennsylvania and lead to large and significant reductions in property values for properties on ground water suggesting that individuals closest to drilling activity are well aware of the water contamination concerns. Therefore, pregnant women close to drilling operations are likely to be aware of the water pollution risks and are not as likely to be exposed through drinking water sources.[4] As reported in the main text, I do not find differences in birth outcomes between residences on public water versus those on ground water. This does not rule out systemic ground or surface water contamination, but is suggestive that the mechanism behind the results is air pollution or maternal stress. Although maternal stress and birth outcomes is an under-developed area of research, there are some recent studies that suggest a relationship between maternal stress and low birth weight and gestational age (Rondo et al., 2003; Dole et al., 2003; Camacho, 2008; Eskenazi et al., 2007; Lindo, 2011). Mothers living closest to drilling activity are most likely to be affected by noise, light and visible aspects of the drilling process, so I cannot rule out maternal stress as an additional factor.

There are many potential mechanisms that are impacting public health and explain the

[4]As with Currie et al. (2013b), I do find larger effects for mothers who are high school dropouts. This may indicate that less educated mothers are not mitigating the risks as effectively as mothers who are better educated. Results are available upon request.

results in this paper.[5] Even with better data, there is unlikely to be just one mechanism or one pollutant that explains the results.

A.3 Additional Robustness Checks

Appendix Table A.3 contains estimates for white mothers only, non-smokers only, mothers aged 19-35 only, mothers born in Pennsylvania only, and estimates for two different designations of drilling intensity (top producing and top drilled counties). For whites, non-smokers and mothers aged 19-35 years, the results are all consistent with the main findings. Using mothers born in Pennsylvania as a proxy for migration, I present results for this group in Panel D and find similar results. Of course, this does not account for migration within Pennsylvania, but 80 percent of the mothers in communities where drilling took place were born in Pennsylvania, compared to 60 percent of mothers in the rest of the state. Finally, my identification strategy uses spud date to define exposure, but shale gas development involves more than individual gas wells. The majority of pollution emitted comes from compressor stations, which are used during the production period that follows drilling. Panels E and F of Appendix Table A.3 allow for comparison between the top 10 producing counties and the top 10 counties with the most wells drilled during my sample. These estimates are slightly larger than the effects estimated in Tables 2.4 and 2.5 suggesting that as drilling and production intensifies, the impacts estimated in this paper may be a lower bound.

[5] See public health discussion papers for more: Finkel et al. (2013); Shonkoff (2012); Mitka (2012); Finkel and Law (2011); Colborn et al. (2011); Schmidt (2011); Shelley (2011).

Table A.1: Impact of Well Location on Low and Term Birth Weight within 15 km

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	Pre-drilling				Pre- and post- drilling			
	Low Birth Weight		Term Birth Weight		Low Birth Weight		Term Birth Weight	
Within 2.5 km of well	-0.00319*	-0.00247	11.04*	12.29*	-0.00401**	-0.00335**	-4.14	3.951
	(0.00178)	(0.00203)	(6.328)	(5.033)	(0.00169)	(0.00157)	(4.774)	(2.975)
Post-drilling					-0.000143	-0.00202	12.04**	13.45***
					(0.00143)	(0.00162)	(5.715)	(4.816)
Within 2.5 km * post-drilling					0.00688*	0.00652*	-22.07*	-23.34**
					(0.00373)	(0.00338)	(11.13)	(10.01)
Sample Size	144127	141127	129781	129781	183314	183314	168673	168673
R^2	0.002	0.021	0.008	0.073	0.002	0.020	0.007	0.073
Maternal Characteristics	no	yes	no	yes	no	yes	no	yes

Notes: Each coefficient is from a different regression. Pre-drilling(post-drilling) refers to births that occur before (after) the spud date of well within 2.5 km. Standard errors are clustered at the mother's residence county. The sample is limited to singleton births and residences within 15 km of a gas well or permit. All regressions include indicators for month and year of birth, their interactions, residence county indicators, an indicator for drilling before birth (defined by closest well), an indicator for specified distance from a well or future well/permit and the interaction of interest reported above. Maternal characteristics include mother black, mother Hispanic, mother education (hs, some college, college), mother age (19-24,25-34, 35+), female child, WIC, smoking during pregnancy, marital status and payment type (private insurance, medicaid, self-pay, other). Standard errors are in parentheses and clustered at the mother's residence county. Source: Author calculations from Pennsylvania Department of Health Vital Statistics. Significance: * p<0.10, ** p<0.05, *** p<0.01

Table A.2: The Effect of Shale Gas Extraction on Birth Weight by Distance

	(1) 0-1 km	(2) 0-1.5 km	(3) 0-2 km	(4) 0-2.5 km	(5) 0-3 km	(6) 0-3.5 km
			Panel A: Low Birth Weight			
Nearby * post-drilling	0.00742	0.00821	0.0127**	0.0136**	0.0115**	0.00912**
	(0.0169)	(0.0102)	(0.00512)	(0.00511)	(0.00510)	(0.00391)
Sample Size	3796	8200	14113	21610	28865	36393
R^2	0.052	0.030	0.023	0.021	0.019	0.019
			Panel B: Term Birth Weight			
Nearby * post-drilling	25.47	-8.326	-38.05*	-49.58***	-30.84**	-29.69**
	(37.01)	(18.87)	(21.49)	(14.04)	(14.20)	(12.59)
Sample Size	3504	7561	13028	19978	26637	33572
R^2	0.123	0.092	0.077	0.075	0.078	0.077

Notes: See Table 2.4. Each panel is a separate regression. All regressions include controls for maternal characteristics and county-time trends. “Nearby” is defined by the distance in the column headings. Source: Author calculations from Pennsylvania Department of Health Vital Statistics. Significance: * p<0.10, ** p<0.05, *** p<0.01.

Table A.3: Robustness Checks, Shale Gas Development on Birth Measures

	(1) Low Birth Weight	(2) Term Birth Weight	(3) Birth Weight	(4) Small for Gestational Age
Panel A: White mothers only				
<2.5 km gas well * Post-drilling	0.0162	-53.3692	-51.5537	0.0202
	(0.005)***	(13.467)***	(12.262)***	(0.009)**
R^2	0.017	0.072	0.057	0.036
Observations	20892	19321	20892	20808
	0.0124			
Panel B: Non-smokers only				
<2.5 km gas well * Post-drilling	0.0124	-47.7803	-49.8992	0.0229
	(0.005)**	(18.577)**	(20.266)**	(0.011)**
R^2	0.012	0.036	0.028	0.016
Observations	15145	14075	15145	15088
Panel C: Mothers aged 19-35 only				
<2.5 km gas well * Post-drilling	0.0184	-70.7524	-67.4247	0.0195
	(0.007)**	(12.282)***	(13.193)***	(0.009)**
R^2	0.017	0.072	0.058	0.036
Observations	17605	16295	17605	17538
Panel D: Mother born in PA only				
<2.5 km gas well * Post-drilling	0.0132	-53.5205	-40.0122	0.0185
	(0.005)***	(17.299)***	(16.914)**	(0.009)*
R^2	0.018	0.076	0.060	0.038
Observations	17491	16163	17491	17424
Panel E: Top 10 producing counties only				
<2.5 km gas well * Post-drilling	0.0165	-50.3268	-43.6648	0.0138
	(0.007)**	(13.436)***	(9.748)***	(0.008)+
R^2	0.021	0.074	0.060	0.037
Observations	15052	13911	15052	15001
Panel F: Top 10 counties with the most drilled wells only				
<2.5 km gas well * Post-drilling	0.0188	-43.6077	-37.3565	0.0154
	(0.004)***	(13.837)**	(12.803)**	(0.009)+
R^2	0.018	0.067	0.052	0.037
Observations	13208	12214	13208	13156
	0.0124			

Notes: See Table 2.4. Each panel is a separate regression. All regressions include controls for maternal characteristics and county-time trends. Source: Author calculations from Pennsylvania Department of Health Vital Statistics. Significance: + p<0.15, * p<0.10, ** p<0.05, *** p<0.01

Table A.4: Summary Statistics For Difference-in-Difference Sample by Water Source

	Sample Means within 2.5 km		T-Stat of
	Ground Water	Public Water	Difference
Characteristics of Birth			
Birthweight	3360.94	3332.85	3.15**
Term Birth Weight	3425.33	3411.07	1.84
Gestation Length	38.76	38.65	3.69***
Premature	0.048	0.059	-3.06**
Low birth weight (LBW)	0.068	0.08	-2.84**
Small for gestational age (SGA)	0.093	0.101	-1.68
APGAR 5 minute	8.892	8.881	0.96
Mother's Demographic Characteristics			
Dropout	0.124	0.109	3.01**
High School	0.297	0.295	0.19
Some college	0.308	0.296	1.73
College plus	0.268	0.297	-3.94***
Teen Mom	0.039	0.05	-3.28**
Mom Aged 19-24	0.25	0.274	-3.28**
Mom Aged 25-34	0.566	0.541	3.23**
Mom Aged 35 and older	0.144	0.135	1.61
Black	0.006	0.031	-10.04***
Hispanic	0.008	0.012	-2.56*
Smoked during pregnancy	0.26	0.311	-7.06***
Married	0.698	0.612	10.84***
WIC	0.358	0.411	-6.71***
Medicaid	0.272	0.343	-9.59***
Private Insurance	0.611	0.553	7.38***
Sample Size	5218	16392	

Source: Author calculations from Pennsylvania Department of Health Vital Statistics. * p<0.10, ** p<0.05, *** p<0.01

APPENDIX B

APPENDIX TO CHAPTER 3: COLORADO

Table B.1: Impact of Well Location on Birth Outcomes- Comparison of Location Fixed Effects

	Birth Weight		Gestation		Low Birth Weight		Premature	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Within 1km * post-drilling	-30.72***	-35.79***	-0.114***	-0.114***	0.0144***	0.0170***	0.0205***	0.0215***
	(8.694)	(11.13)	(0.0148)	(0.0408)	(0.00175)	(0.00543)	(0.00287)	(0.00457)
Sample Size	20,687	20,687	20,687	20,687	20,687	20,687	20,687	20,687
R^2	0.082	0.055	0.049	0.025	0.057	0.025	0.045	0.021
County Fixed Effects	yes	no	yes	no	yes	no	yes	no
Zip Code Fixed Effects	no	yes	no	yes	no	yes	no	yes
Standard Errors Clustered By	county	zip	county	zip	county	zip	county	zip

Note: Each coefficient is from a different regression. Post-drilling refers to births that occur after the spud date of the closest well. Standard errors are clustered according to the location fixed effect. The sample is limited to a four-year window surrounding drilling (i.e. 2 years prior and 2 years after), residences within 5 km of a well and singleton births. All regressions include maternal characteristics, quarter and year of birth, residence county(zip), and quarter*year fixed effects. County-fixed effects regressions also include county*quarter*year fixed effects. See Table 3.4 for covariates included. Source: Author calculations from Colorado Department of Public Health and Environment Vital Statistics. * $p<0.10$, ** $p<0.05$, *** $p<0.01$

Table B.2: The Effect of Extraction on Birth by Distance

	0-0.5 km (1)	0-1 km (2)	0-1.5 km (3)	0-2 km (4)
Panel A: Birth weight				
Nearby * post-drilling	-8.705	-35.79***	-25.55+	-4.575
	(20.07)	(11.13)	(15.88)	(11.65)
Sample Size	20,687	20,687	20,687	20,687
R^2	0.054	0.055	0.054	0.054
Panel B: Gestation				
Nearby * post-drilling	0.0134	-0.114***	-0.0868**	0.00534
	(0.0734)	(0.0408)	(0.0385)	(0.0601)
Sample Size	20,687	20,687	20,687	20,687
R^2	0.025	0.025	0.025	0.025
Panel C: Low birth weight				
Nearby * post-drilling	-0.00170	0.0170***	0.00959*	0.000582
	(0.0103)	(0.00543)	(0.00544)	(0.00583)
Sample Size	20,687	20,687	20,687	20,687
R^2	0.024	0.025	0.024	0.024
Panel D: Premature birth				
Nearby * post-drilling	0.00783	0.0215***	0.0149**	0.000847
	(0.0109)	(0.00457)	(0.00585)	(0.00832)
Sample Size	20,687	20,687	20,687	20,687
R^2	0.020	0.021	0.020	0.020

Note: Each coefficient is from a different regression. Post-drilling refers to births that occur after the spud date of the closest well. Nearby is defined by the distance in each column. Standard errors are clustered at the mother's residence zip code. The sample is limited to a four-year window surrounding drilling (i.e. 2 years prior and 2 years after), residences within 5 km of a well and singleton births. All regressions include maternal characteristics, quarter and year of birth dummies, residence zip code dummies, and quarter*year fixed effects. See Table 3.4 for covariates included. Author calculations from Colorado Department of Public Health and Environment Vital Statistics. + p<0.15, * p<0.10, ** p<0.05, *** p<0.01

Table B.3: Impact of Well Location on Birth Outcomes, 2007-2011: Comparison of Covariates

	Birth Weight		Gestation		Low Birth Weight		Premature	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Within 1km * post-drilling	-33.84***	-30.70***	-0.120***	-0.103***	0.0218***	0.0203***	0.0139*	0.0116
	(10.53)	(9.425)	(0.0278)	(0.0262)	(0.00292)	(0.00337)	(0.00776)	(0.00849)
Sample Size	9,719	9,719	9,718	9,718	9,719	9,719	9,718	9,718
R^2	0.072	0.075	0.040	0.045	0.054	0.057	0.032	0.035
Maternal Characteristics	yes	yes	yes	yes	yes	yes	yes	yes
Income/insurance covariates		yes		yes		yes		yes

Note: Each coefficient is from a different regression. Post-drilling refers to births that occur after the spud date of the closest well. Standard errors are clustered at the mother's residence county. The sample is limited to a four-year window surrounding drilling (i.e. 2 years prior and 2 years after), singleton births and the years 2007-2011. All regressions include maternal characteristics, indicators for quarter and year of birth, residence county indicators and interactions between quarter, year and county. See Table 3.4 for covariates included. Author calculations from Colorado Department of Public Health and Environment Vital Statistics. * $p<0.10$, ** $p<0.05$, *** $p<0.01$

Table B.4: Impact of Well Location on Birth Outcomes within 1 km vs. 1-2 km, 2000-2011

	Birth Weight		Gestation		Low Birth Weight		Premature	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Panel A: Pre-drilling (2 km)								
Within 1 km of well	54.23***	46.54***	0.0934**	0.105***	-0.0128*	-0.0156***	-0.0216***	-0.0198***
	(12.53)	(6.025)	(0.0444)	(0.0142)	(0.00744)	(0.00252)	(0.00532)	(0.00283)
Sample Size	7,095	7,095	7,097	7,097	7,095	7,095	7,097	7,097
R^2	0.026	0.071	0.023	0.060	0.018	0.075	0.019	0.062
Maternal Characteristics	no	yes	no	yes	no	yes	no	yes
Panel B: Pre- and post- drilling (2 km)								
Within 1 km * post-drilling	-37.85***	-35.22***	-0.107**	-0.115**	0.0190***	0.0182***	0.0239***	0.0243***
	(10.71)	(10.78)	(0.0458)	(0.0445)	(0.00531)	(0.00486)	(0.00447)	(0.00455)
Sample Size	12,079	12,079	12,080	12,080	12,079	12,079	12,080	12,080
R^2	0.019	0.063	0.017	0.030	0.013	0.030	0.015	0.027
Maternal Characteristics	no	yes	no	yes	no	yes	no	yes

Note: Each coefficient is from a different regression. Pre-drilling (post-drilling) refers to births that occur before (after) the spud date of the closest well. Standard errors are clustered at the mother's residence zip code. The sample is limited to a four-year window surrounding drilling (i.e. 2 years prior and 2 years after), residences within 2 km of a well and singleton births. All regressions include maternal characteristics, quarter and year of birth, residence zip code, and quarter*year fixed effects. See Table 3.4 for covariates included. Source: Author calculations from Colorado Department of Public Health and Environment Vital Statistics.
* $p<0.10$, ** $p<0.05$, *** $p<0.01$

Table B.5: Impact of Well Location on Birth Outcomes Using Conception Date

	Birth Weight (1)	Gestation (2)	Low Birth Weight (3)	Premature (4)
Within 1 km * post-drilling	-42.04***	-0.115**	0.00931	0.0124***
	(12.35)	(0.0456)	(0.00711)	(0.00423)
Sample Size	20,687	20,687	20,687	20,687
R^2	0.055	0.025	0.025	0.020

Note: Each coefficient is from a different regression. Post-drilling refers to births that occur after the spud date of the closest well. Standard errors are clustered at the mother's residence zip code. The sample is limited to a four-year window surrounding drilling (i.e. 2 years prior and 2 years after), residences within 5 km of a well and singleton births. All regressions include maternal characteristics, quarter and year of birth dummies, residence zip code dummies, and quarter*year fixed effects. See Table 3.4 for covariates included. Author calculations from Colorado Department of Public Health and Environment Vital Statistics.
* p<0.10, ** p<0.05, *** p<0.01

APPENDIX C
APPENDIX TO CHAPTER 4: TEXAS

Table C.1: Differences in Average Maternal Characteristics of Births Close to Well Locations

	Characteristic of Mother						
	Teen Mom	Dropout	Black	Smoked	Hispanic	Married	Current Risky
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
	Panel A: Cross-sectional differences in characteristiscs						
shale	0.0604***	-0.0532***	-0.0899***	0.0223***	-0.454***	0.118***	-0.0507***
	(0.00104)	(0.00192)	(0.00185)	(0.000896)	(0.00247)	(0.00191)	(0.00108)
Sample Size	1,012,445	1,164,527	1,012,445	1,164,527	1,012,445	1,012,445	1,012,445
R^2	0.025	0.286	0.169	0.043	0.249	0.113	0.023
	Panel B: Differences in characteristiscs for analysis sample using DD estimator						
shale * years 1998-2001	0.00216	-0.000813	0.00709*	-0.00595***	-0.0121**	-0.00170	-0.00663*
	(0.00237)	(0.00469)	(0.00400)	(0.00229)	(0.00563)	(0.00386)	(0.00343)
shale * years 2001-2004	-3.73e-05	0.00816	0.0117	-0.00880***	-0.0160	-0.0688***	-0.0277***
	(0.00335)	(0.0103)	(0.00930)	(0.00318)	(0.0130)	(0.00893)	(0.00527)
shale * years 2004-2008	0.000689	0.0803***	0.0169	-0.0316***	-0.0104	-0.0106	-0.00698
	(0.00393)	(0.0184)	(0.0126)	(0.00512)	(0.0169)	(0.00978)	(0.00506)
Sample Size	1,012,445	1,012,445	1,012,445	1,012,445	1,012,445	1,012,445	1,012,445
R^2	0.025	0.281	0.169	0.037	0.249	0.113	0.023

Notes: Each coefficient is from a different regression. All regressions include indicators for month and year of birth, their interactions and residence zip code indicators. Source: Author calculations from Texas Department of State Health Services Vital Statistics. Significance: * p<0.10, ** p<0.05, *** p<0.01.

Table C.2: Impact of Well Location on Birth Outcomes

	Term Birth Weight (1)	Term Birth Weight (2)	Low Birth Weight (3)	Low Birth Weight (4)	Gestation (5)	Gestation (6)	Premature (7)	Premature (8)
shale	39.00***	25.28***	-0.0353***	-0.00307*	0.244***	-0.0345*	-0.0208***	0.00723***
	(5.679)	(4.655)	(0.00171)	(0.00173)	(0.0232)	(0.0201)	(0.00186)	(0.00194)
years 1998_2001	-16.77*	-19.06*	0.00224	0.00201	-0.200***	-0.191***	-0.00226	-0.00218
	(9.843)	(9.861)	(0.00402)	(0.00410)	(0.0458)	(0.0461)	(0.00443)	(0.00449)
years 2001_2004	-37.43***	-43.37***	0.00710	0.00913**	-0.355***	-0.362***	0.0175***	0.0185***
	(9.807)	(9.744)	(0.00436)	(0.00436)	(0.0496)	(0.0519)	(0.00475)	(0.00493)
years 2004_2008	-44.99***	-21.47	0.0107***	0.0161	-1.002***	-0.730***	0.0211***	0.0366**
	(9.184)	(33.68)	(0.00393)	(0.0155)	(0.0367)	(0.189)	(0.00433)	(0.0159)
shale * years 1998-2001	-0.899	-2.679	-0.000374	0.00121	-0.0781**	-0.0872***	0.00190	0.00259
	(5.675)	(5.854)	(0.00277)	(0.00292)	(0.0323)	(0.0334)	(0.00289)	(0.00308)
shale * years 2001-2004	-11.36	-11.62*	-0.000127	0.00125	-0.0829**	-0.0889**	-0.00240	-0.00147
	(7.092)	(6.080)	(0.00268)	(0.00275)	(0.0377)	(0.0366)	(0.00285)	(0.00305)
shale * years 2004-2008	-13.95*	-13.43**	0.000739	0.00112	-0.0770***	-0.0802***	-0.00291	-0.00185
	(7.372)	(6.052)	(0.00176)	(0.00183)	(0.0253)	(0.0224)	(0.00235)	(0.00241)
Observations	1,064,308	951,573	1,164,494	1,040,364	1,100,583	983,504	1,164,432	1,040,313
R-squared	0.009	0.061	0.004	0.037	0.024	0.054	0.004	0.026
Maternal Characteristics	no	yes	no	yes	no	yes	no	yes

Notes: Each coefficient is from a different regression. The sample is limited to singleton births. Shale is an indicator for zip codes with gas wells within the zip code boundary. All regressions include indicators for month and year of birth, their interactions, and residence zip code indicators. Maternal characteristics include mother black, mother Hispanic, mother education (hs, some college, college), mother age (19-24,25-34, 35+), female child, smoking during pregnancy, marital status, parity, previous risky pregnancy, current risky pregnancy, and prenatal care. Standard errors are in parentheses and clustered at the mother's residence zip code.
* p<0.10, ** p<0.05, *** p<0.01

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